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## DREDGING FOR ENVIRONMENTAL BENEFIT: MODELS OF CIRCULATION AND FLUSHING DYNAMICS IN THE PROVIDENCE RIVER ESTUARY

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DREDGING FOR ENVIRONMENTAL BENEFIT:  
MODELS OF CIRCULATION AND FLUSHING DYNAMICS IN THE  
PROVIDENCE RIVER ESTUARY

BY

GRACE ELIZABETH MEDLEY

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

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UNIVERSITY OF RHODE ISLAND

2019

MASTER OF SCIENCE THESIS  
OF  
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2019

## **ABSTRACT**

In estuarine dynamics, circulation in the form of mixing and exchange have a direct link to the water quality. Edgewood Shoals is a highly anthropogenically impacted region of the Providence River, bordered by three cities, and receives the outfall from six wastewater treatment facilities. Edgewood Shoals also experiences low dissolved oxygen levels during the summer months. The Edgewood Shoals is classified as a circulation-restricted zone, where hydrodynamic exchange is limited due to the steep bathymetric gradient created by an adjacent federal shipping channel. The US Army Corps of Engineers (USACE) is in the process of determining if there are options for placement of a CAD (Confined Aquatic Disposal) cell for contaminated sediment disposal in regions of the Providence River. Edgewood Shoals is under consideration for the placement one of these CAD Cells. The purpose of this project is to first model an Edgewood Shoals reference case, verify this model run against existing hydrodynamic data, and finally to use the model to alter the bathymetry of the Shoal in a way that would enhance hydrodynamic exchange. Dredging scenarios created in this study aim to cover two objectives. The first is to increase the amount of exchange between Edgewood Shoals and the adjacent deep channel of the Providence River, improving the flushing dynamics on Edgewood Shoals. The second is to achieve this goal while remaining practical for use by USACE. The Regional Ocean Modeling System is applied to investigate these changes to circulation using simulated drifters and numerical dyes to characterize local residence times and exchange. It is evident from this study that the model is describing flushing times that are unrealistically fast. Therefore, results are presented as a

percent-change from the reference case. Results indicate that an east-west oriented channel dredged in the northern section of the Shoal decreases the flushing time by 60%, and filling in the Port Edgewood Turning Basin decreases the flushing time by 30%.

## **ACKNOWLEDGMENTS**

First off, I'd like to thank my advisor Dr. Chris Kincaid for the guidance and endless positivity throughout this process. Thank you most of all for teaching me to love and appreciate math and applied fluid dynamics. To Mike Walsh at USACE, thank you for your input throughout the report-writing process. To my funding sources, USACE and the Webb Family Endowment for Oceanography, thank you for providing the opportunity to attend GSO and complete my research fully-funded. To David, Meredith and Rhonda, thank you for your support in navigating a coherent path to graduation. Finally, to my friends and family, especially Nick, Mary-Kate, Lisa, Casey, Melanie, Sarah, Nicole, Loes, Kevin and so, so many others: thank you for the endless support, excellent conversation, and for keeping me sane over these past two years.

## **DEDICATION**

This thesis is dedicated to my father, Bruce G. Medley (11/10/1951 – 5/17/2017) who taught me to love and respect Narragansett Bay. I've carried the memories of growing up on the water and lessons you've taught me about the Bay with me throughout this process.

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# **MANUSCRIPT**

## **1. INTRODUCTION**

In December, 2017, the United States Army Corps of Engineers (USACE) New England District provided the performance work statement for the URI Graduate School of Oceanography to conduct hydrodynamic modeling work as part of the Providence River and Harbor Dredged Material Management Plan (PRHDMMP). This modeling work was completed for the upcoming maintenance dredging cycle of the Federal Ship Channel in Narragansett Bay. The PRHDMMP is the blue-print for disposal alternatives for unsuitable material resulting from maintenance dredging operations. This includes the placement of Confined Aquatic Disposal (CAD) Cells within Narragansett Bay.

Integrated into their plan is a CAD Cell in a shallow, 1km-wide area of the Providence River known as Edgewood Shoals (Figure 1a, 1b). Edgewood Shoals is known for intermittent hypoxia due to weak hydrodynamic exchange with the rest of Narragansett Bay. The circulation that severely restricts the lateral exchange of water between the Shoal and the Ship Channel has been studied as a result of 15+ years of observational data collection. The purpose of this project is to use these data to augment the results of a 3-dimensional hydrodynamic model in order to analyze the tidal and non-tidal patterns of flow on Edgewood Shoals, and identify the specific pathways through which exchange of chemical constituents with the main estuary occurs. Using these results, I propose a series of bathymetric modifications that

enhance these existing exchange pathways, to be implemented as part of the 2019 PRHDMMP.

## 2. BACKGROUND

### *2.1 Circulation Dynamics and Dissolved Oxygen:*

It has been well-established that the physical processes of an estuary or sub-estuary have a direct link to the water quality (Stram et al., 2005 (Rio Chone Estuary); Stanley and Nixon 1992 (Pamlico Estuary); Yin et al., 2005 (Pearl River Estuary); Zhu et al. 2015 (Tampa Bay Estuary); Biocort, 1992 (Chesapeake Bay Estuary). Dissolved oxygen (DO) depletion, also known as hypoxia, occurs when large blooms of photosynthetic microalgae increase the demand for oxygen in a body of water. Hypoxia, or the decrease in dissolved oxygen in the water column to a level of less than 3 mg/l, has significant impacts on the ecology of the estuary. Increases in biological productivity leads to amplified respiration rates, resulting in a dissolved oxygen minimum zone that occurs beneath the bloom in subpycnoclinal waters. Causes behind these isolated blooms are a combination of nitrogen loading from anthropogenic sources (Saarman et al. 2008), and weak lateral movement of bottom water within an estuary or sub-estuary with the main body of the estuary (Abdelrhman, 2005).

Weak lateral movement of a water column is an important factor in dissolved oxygen distribution in an estuary (Saarman et al. 2008, Abdelrhman, 2005, Deacutis et al, 2006, Deacutis, 2008 Brietburg, 2002). Water has two ways of being re-oxygenated following periods of blooms and hypoxia-causing biological activity. This water can be re-aerated at the surface, or can be advected in from another place where it was recently interacting with surface water. In this region of Narragansett Bay, re-oxygenated water is sourced from either the interaction with local surface water, or the

lower Bay, where water is more likely to have been mixed. The sub-regions of the Providence River are susceptible to reductions in the lateral transport of water from the adjacent Ship Channel, which is the main conduit for lower-Bay water. Brietburg (2002) identified local residence times as being one of the most important factors influencing dissolved oxygen concentrations. Residence times are highly attributed to local hydrographic and geographic features, and can ultimately determine the water quality of a sub-region. Circulation patterns are the controlling mechanisms behind the residence times of a subregion of an estuary (Fujjuwara et al., 2002). Without regular flushing, water that sits in an area of the bay has the ability to become hypoxic, and a single event can advect this low-oxygen water to a different part of the bay.

Deacutis et al. (2006) found that dissolved oxygen minima in highly stratified water columns in the Providence River rivaled those of the less-stratified water column of Greenwich Bay, RI, where residence times were determined to be longer. A highly density-stratified water column inhibits mid-water column to low-water column parcels from interacting with surface water to experience oxygen replenishment. Near bottom, or subpycnocline hypoxia almost always occurs during periods of highly stratified conditions (Brietburg, 2002).

## *2.2 Dissolved Oxygen Dynamics on Edgewood Shoals, Providence River*

In a Bay-wide low dissolved oxygen event in 2001, the oxygen minimum zone of the Providence River occurred beneath the shallow pycnocline on Edgewood Shoals (Deacutis et al. 2006). Bottom water in this case was severely hypoxic ( $<0.8$  mg/l) to borderline anoxic ( $<0.1$  mg/l), and has lower dissolved oxygen levels than bottom water in the adjacent Ship Channel. During this time period in which the low-

dissolved oxygen event occurred, the conditions of the water column were highly stratified.

Between 2005 and 2014, dissolved oxygen surveys were performed at 77 locations throughout the Upper Bay and the Providence River (<http://www.geo.brown.edu/georesearch/insomniacs>). Data from the Edgewood Shoals locations in these surveys indicated dissolved oxygen levels that were borderline hypoxic to acute hypoxic (DO levels of 2.3 mg/l or less) in 2006, 2008, 2009, 2010, 2012 and 2013 during the months of July and August. The circulation pattern leading to a highly stratified water column on Edgewood Shoals is to blame for the higher probability of low-oxygen events. It is believed that there is a direct link between the hydrodynamic disconnect between Edgewood Shoals and the adjacent Ship Channel, and high probability of low-oxygen events that occur there. It is believed that the system can be altered in such a way to allow for a higher rate of water exchange with the Ship Channel, and a higher rate of vertical mixing. If these factors can be improved, the health of the ecosystem on Edgewood Shoals will improve in a significant way.

### *2.3 Study Area: Edgewood Shoals*

Edgewood Shoals is a relatively shallow Shoal (~2 meters) in the Providence River in Upper Narragansett Bay. The 1km-1.5 km Shoal is defined as anything to the west of the main Providence River shipping channel to the south of Fields Point and to the north of the Pawtuxet River outfall. A steep bathymetric gradient separates the main body of a maintained 10-12-meter deep Ship Channel from the shallow shelf of Edgewood Shoals. Due to this steep gradient and the added influence of Field's Point,



a man-made shoreline, Edgewood Shoals is shown through data and numerical modeling that hydrodynamic exchange with the Ship Channel is severely restricted.

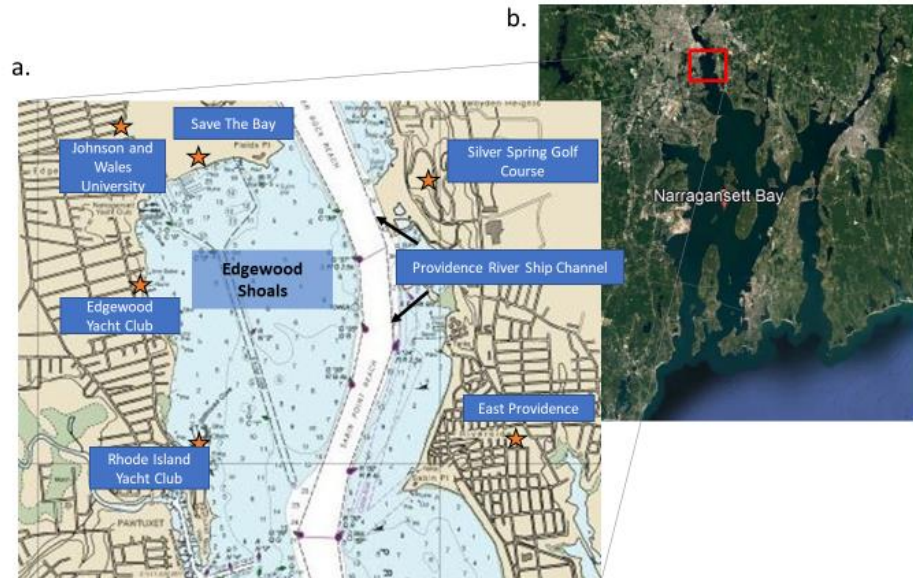


Figure 1 (a.) A nautical chart (NOAA OCS Chart # 13224) outlining major features of Edgewood Shoals. Marked with orange stars are locations on the shores of the Shoal, and marked with black arrows is the location of the maintained Providence River Ship channel. (b.) A satellite image of Narragansett Bay with a red box outlining the location of Edgewood Shoals.

The section of the bay that comprises Edgewood Shoals is subject to significant anthropogenic pressures, including bacterial contamination, pollution from heavy metals and excessive nutrient loading. This nutrient loading is sourced from a combination of land-surface runoff, wastewater treatment facility discharge, and the discharge contribution of local tributaries (Deacutis, 2008). The shores of Edgewood Shoals are composed of the cities of East Providence (East shore), Providence (North shore) and the cities of Cranston (West shore) and Warwick to the south and west. In addition to surface runoff from these cities, the shoreline of Edgewood Shoals harbors two Wastewater Treatment Facilities (WWTF) (figure 2) in the cities of East Providence and Providence, Fields Point WWTF and the East Providence WWTF, and

takes on runoff from the Pawtuxet River, which is composed of surface runoff as well as the discharge of three more WWTF's, The City of Warwick WWTF, City of Cranston WWTF and Town of West Warwick WWTF.

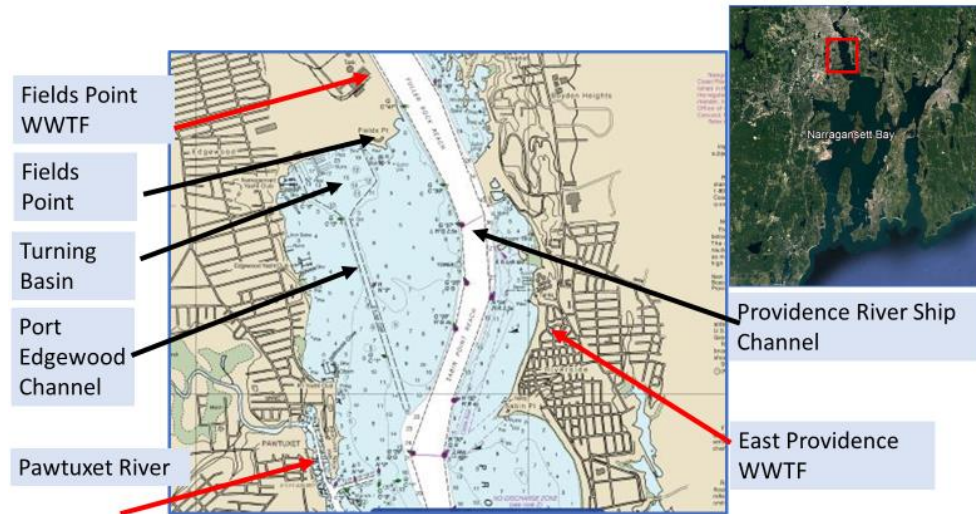


Figure 2. A nautical chart (NOAA OCS Chart # 13224) of Edgewood Shoals with arrows outlining major features on the Shoal. Geographic and bathymetric features are outlined with black lines while the wastewater treatment facilities and river outfall are outlined with red arrows.

### 2.3 Circulation on Edgewood Shoals: Previous Studies

Circulation in the Providence River Estuary has been studied previously by Bergondo (2005), Rogers (2008), LaSota (2009) and Balt (2012). Acoustic Doppler Current Profiler (ADCP) and Tilt Current Meter (TCM) studies in 2005 and 2010 (Bergondo and Kincaid 2005, Kincaid 2012), respectively, provide a spatially and temporally detailed observational foundation for tidal and residual circulation patterns throughout the Providence River. This includes detailed coverage of Edgewood Shoals. Additionally, scaled analogue model studies of Edgewood Shoals were completed at the Australian National University in Canberra, ACT (Kincaid, 2008 unpublished data). The combination of moored and underway ADCP deployments

(Kincaid, 2001; Kincaid and Bergondo, 2005), a network of 22 TCM's (Kincaid, 2012) and a Regional Ocean Modeling System (ROMS) parameter validation study (Rogers, 2008; Kincaid, 2012) characterize hydrodynamic patterns in this region for both instantaneous (tidal) and residual (tidal cycle frequencies removed) flows. Residual flow patterns observed in both numerical and laboratory models include a strong net southward flow in the surface water of the Providence River Ship Channel, a northward deep return flow in the bottom and eastern edge of the Ship Channel, and the formation of a persistent clockwise gyre on Edgewood Shoals, as is discussed below.

#### *2.4 Dispersion Studies on Edgewood Shoals and the Providence River Using an ADCP (July 2005-October 2005)*

Three moored Acoustic Doppler Current Profiler's (ADCP) were deployed in the summer of 2005 to collect observational data for four months in the Providence River and on Edgewood Shoals. Additionally, three underway ADCP surveys were completed during the same time-frame over one tidal cycle to capture the spatial velocity structure of the water column. This work was funded by the Narragansett Bay Commission and was completed by URI Graduate School of Oceanography researchers. RD-Instruments Workhorse ADCP's were used during this deployment. ADCP's emit a pulse of sound that will return to the transducer after interacting with particulates in the water column. The doppler shift in the returned pulses determine the velocity components of the water column (C. Kincaid, pers. comm. August 2017). The purpose of the surveys and modeling work completed for the Narragansett Bay Commission in 2005 was to compile new observational data, which when combined

with numerical modeling using the then-current version of the Narragansett Bay ROMS model would help to verify modeled circulation and transport in the upper regions of the Bay.

The results from these observational surveys indicated that there are high flow velocities present in the main channel just off of Edgewood Shoals, with a sharp decrease in the flow over the Shoals, including areas where the flow reverses. This ‘gyre-like’ flow pattern is indicative of a sharp circulation disconnect between Edgewood Shoals and the Ship Channel. This pattern is understood to be created by a deep, man-made channel along a shallow Shoal, where flow is disrupted due to bathymetric irregularities. Figure 3 is a sample of the observational data collected during the underway ADCP survey in July of 2005. Deep, fast-moving return flow is observed during flood and slack tides in the Ship Channel. Figure 3 also captures the steep bathymetric gradient, or the bathymetric irregularity, that occurs between the shallow Shoal of two meters and the maintained Providence River Shipping Channel of roughly 12 meters. In these data, collected over one complete tidal cycle, there is a continuous trend of residual northward flow on the western side of the Shoal, and residual southward flow on the eastern side of the Shoal. This observation provides a key piece of information regarding Edgewood Shoal’s inability to flush as quickly as the Ship Channel. If the Shoal were to flush at the same rate as the ship channel, a reverse in flow and decrease in flow velocity would not be observed in the ADCP data. ROMS model results were relatively consistent with the field observations from this 2005 ADCP deployment (Bergondo and Kincaid, 2005).

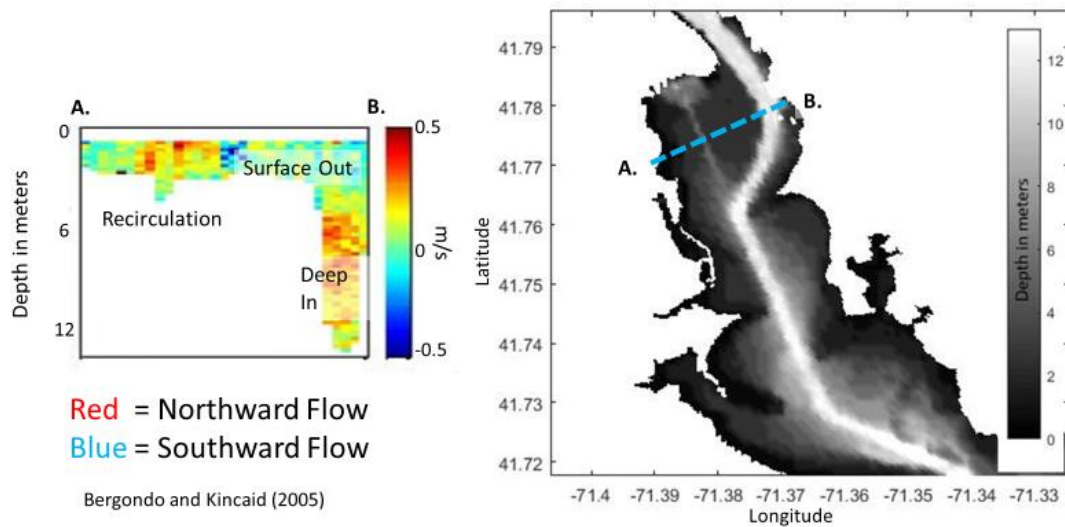


Figure 3. A sample of observational data collected from the second underway ADCP survey completed in July, 2005 (Bergondo and Kincaid, 2005), from a late flood tide. On the color contour plot, blue indicates southward flow, and red indicates northward flow. Depth is measured in meters below Mean Sea Level (MSL), zero being the water surface. The blue dotted line marks the beginning (A) and end (B) of the transect. Classic estuarine flow is observed in the Ship Channel (surface water out, deep water in) whereas recirculation occurs on the circulation-restricted Shoal.

### 2.5 Study: Analog Model of Edgewood Shoals, 2008

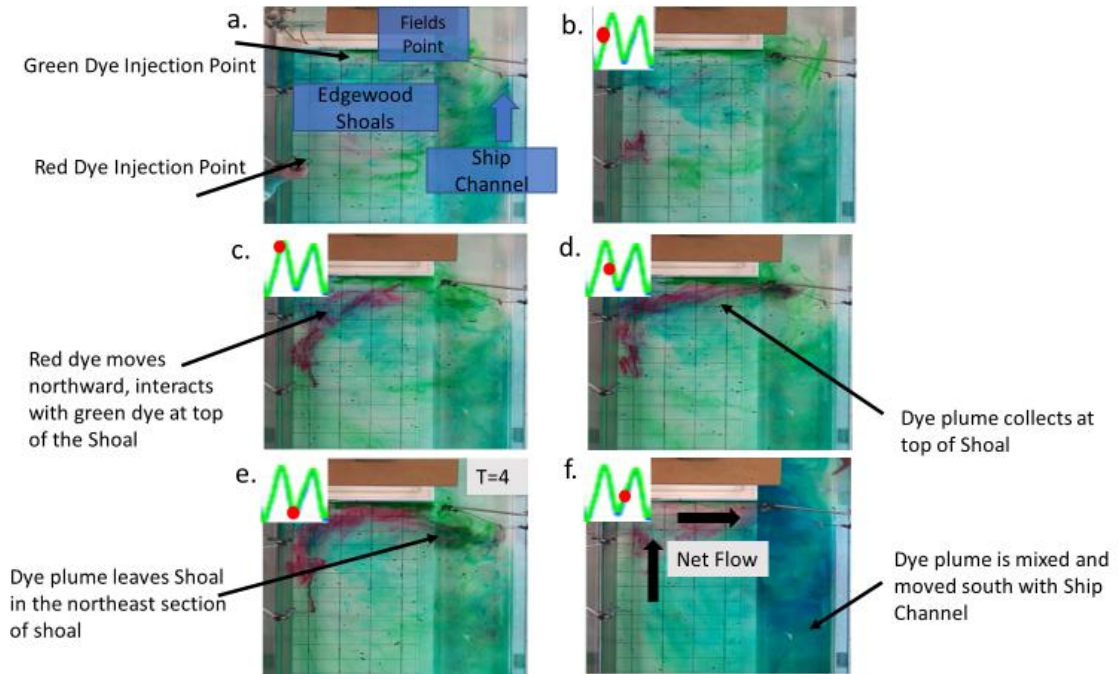


Figure 4. A top-view of a time-series of lab model observations over one tidal cycle collected from the analogue experiments conducted at the Geophysical Fluid Dynamics Laboratory at Australian National University (ANU) for Edgewood Shoals (Kincaid et al, 2008, unpublished data). Red and green dye were both injected into the constant-density water at the surface. Net flow observed travels towards the top of the tank, collects at the top of the tank, then flows off of the Shoal in the area just to the south of “Fields Point” in a jet-like formation.

In fluid dynamics, a theoretical circulation gyre can be caused by the influence of a jet that meets a sudden, abrupt increase of the cross-sectional area of the available channel space (Kincaid, 2012). It is observed that the Providence River is narrow to the north of Field’s Point, and widens sharply just to the south of Field’s Point creating the Shoals. This pattern of a theoretical circulation gyre was observed in scaled laboratory-based experiments (figure 4) of the Providence River as it widens into the Shoals. These experiments were performed at the Geophysical Fluid Dynamics Laboratory at Australia National University (Kincaid pers. Comm 2017;

Balt, 2011). This scaled laboratory model simulated the Providence River Ship Channel-Edgewood Shoals break with only tidal forcing, from a pump at either end of the tank. It is important to note that the bathymetry in this laboratory model is simplified, and the only major features represented are the Ship Channel and the Shoal. For simplification, the Port Edgewood Turning Basin and the Port Edgewood Channel (PEC) are left out of the model. Additionally, this model is vertically homogeneous, and does not represent two-layer flow in the Ship Channel or on Edgewood Shoal.

These assumptions being considered, a few key circulation characteristics of the Shoal are brought to light by this model. With only tidal forcing, the model shows the net flow as having a persistent clock-wise gyre formation. It also shows the circulation disconnect between the circulation in the Ship Channel and the Shoal. The water in the Ship Channel is observed to flush tidally in a north-south direction, eventually flowing down the Bay, while the flushing pattern on the Shoal is more complex. This pattern is also clearly visible in the TCM observations from 2010, as well as the ADCP deployments in 2005.

The analog model indicates that there is a key exit pathway for chemical constituents on Edgewood Shoals (indicated in the experiment by red and green dye in figure 4). This exit pathway at the top, northeast section of the Shoal is indicated by plumes of dye in the experiment that travel along the upper edge of the Shoal (immediately to the south of Fields Point), and are pushed into the Ship Channel, where they are then transported down-bay. According to the observations from the

model this collection of dye occurs during the flood, and the eastward push of dyes off of the Shoal occurs at, and immediately after the beginning of the ebb tide.

#### *2.6 Study: Tilt Current Meter Deployment on Edgewood Shoals, Spring 2010*

Edgewood Shoals is understood from the 2005 ADCP deployment, and from observations from the analogue model at ANU, to be an area of hydrodynamic disconnect between fast-moving waters of the Ship Channel and the shallows of the Shoal. In March of 2010, a network of 21 Tilt Current Meters (TCM's) was deployed in Edgewood Shoals by GSO MS Student C. Balt as part of a project funded by the Narragansett Bay Commission (Balt, 2011), to further investigate these flow patterns. A Seahorse Tilt Current Meter (Manning and Sheremet, 2009) is an instrument that consists of a solid, grounding base that is connected by a soft membrane to a buoyant PVC pipe. The connecting membrane allows the pipe to tilt in the direction of the flow of water. An accelerometer sensor is connected to the top of the PVC pipe and records the angle of that tilt. The meters are calibrated in a laboratory setting that enables users to determine the coefficients necessary for converting the PVC pipe direction of tilt and tilt angles to N-S, E-W velocity components and their magnitudes, respectively.



a.

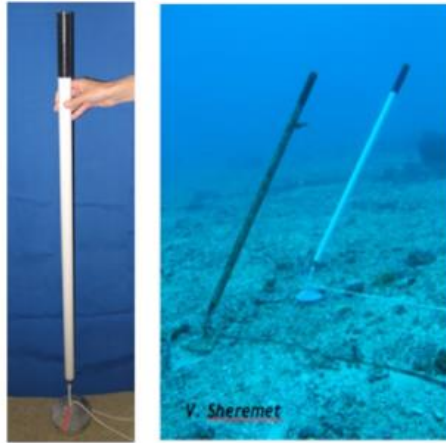


Image: Kincaid 2012

b.

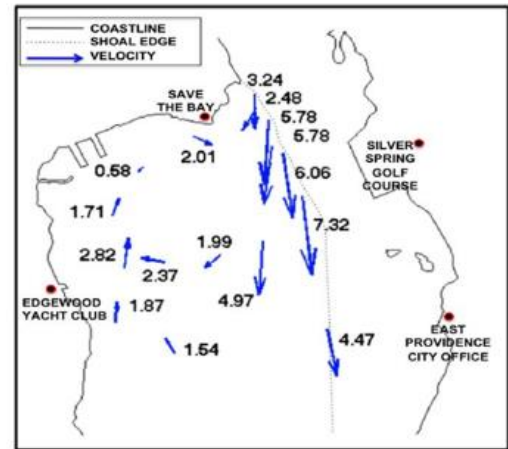


Image: Balt, 2012

Figure 5 (a.) An image of a tilt current meter (un-deployed and deployed) designed by URI marine research associate V. Sheremet. (b.) An image of the net residual circulation patterns on Edgewood Shoals from the observational data collected during the Spring of 2010 (Balt, 2012). Blue arrows indicate averaged flow over the 52- day deployment, in cm/s.

Over the course of the 52 days, the temporal-mean pattern of circulation indicated net-northward, weak flow on the west side of the Shoal, and net-southward, stronger flow on the east side of the Shoal (figure 5b). The flow in the Turning Basin was observed to have the lowest temporal-mean velocity, at 0.58 cm/s. The highest temporal-mean flow was observed by the TCM closest to the Ship Channel, with a southward velocity of 7.32 cm/s.

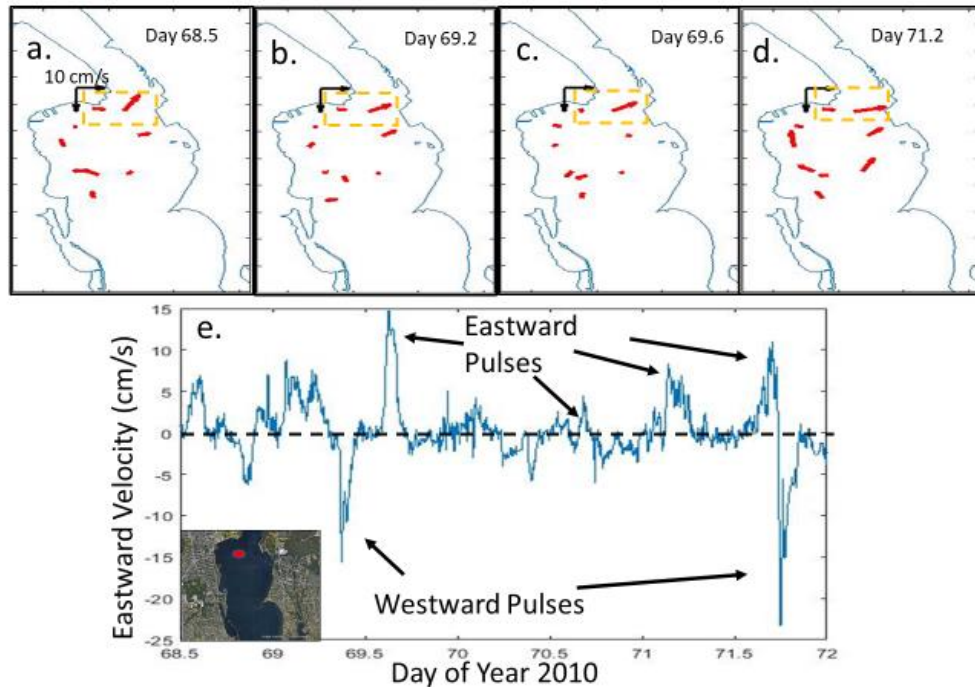


Figure 6. TCM instantaneous velocity observations indicating a pulse of water that forms near the top of Edgewood Shoal at velocities greater than 10 cm/s. This pattern occurs on day (a.) 68.5, (b.) 69.2, (c.) 69.5, and (d.) 71.2 of the 52-day deployment in March-May, 2010. The yellow box indicates the location on the Shoal where there is a persistent pulse of water towards the east, off of the Shoal and into the Ship Channel. (e.) Time-series of eastward flow from a single TCM in the section of the Shoal to the south of Fields Point, over 3.5 days during the 2010 deployment. An eastward pulse is visible in the observations during specific points in the tidal cycle. The inset map shows the location of the TCM (Google Earth).

Over the course of the 52-day deployment, a key pattern emerges in the instantaneous data from the TCM's. During the slack before ebb during every tidal cycle (four of which are pictured in figure 6), there is a pulse of water to the east just to the south of Fields Point. A time-series of this flow in the corner off Edgewood Shoal to the south of Fields Point is pictured in figure 6e. This water is pulsed from the Turning Basin, and the eastward pattern carries it to the Ship Channel where it is flushed down-bay. This jet-like feature is crucial to the residual gyre formation, and is roughly 50-100 meters wide from estimates. This pulse of eastward flow is also short-lived, ceasing shortly after the ebb begins and the velocities from the Ship Channel re-

enhance the hydrodynamic disconnect between the Shoal and the Ship Channel. If this persistent pathway can be enhanced, it has the capability of producing an increase in exchange between the waters in the Ship Channel and the Shoal.

None of the previous studies on Edgewood Shoals have numerically modeled the flushing of water and exchange flows on Edgewood Shoals under real environmental forcing parameters. This project focuses on the tidal and residual recirculation patterns on Edgewood Shoals, and how they combine to severely limit the hydrodynamic exchange with the adjacent Ship Channel. This study also focuses on specific points in the tidal cycle when the Shoal has the capability of exchanging with the Ship Channel, and the key pathways along which this exchange occurs. With the dynamics of the system in mind, a series of bathymetric alterations are designed to enhance these existing exchange pathways, and use a numerical model to test these scenarios.

### *2.7 Impacts of Dredging on Estuarine Circulation*

Bathymetric modifications by dredging can be grouped into four categories. Channel deepening, channel widening, channel creation, and fill. The impacts of dredging on estuarine circulation have been heavily studied in Tampa Bay, FL in reference to maintenance dredging projects for their shipping lanes (Zhu et al, 2014, Goodwin, 1987). These studies have exemplified that widening and deepening the main shipping channel in Tampa Bay, FL will increase the tidal range, and decrease the tidal phase from the mouth to the head of the bay. More importantly, it was discovered that widening and deepening channels will cause a positive shift in non-tidal, or residual circulation (Goodwin, 1987). Goodwin (1987) finds that with

deepening and widening of channels in shallow areas, increasingly rapid transfer of dissolved chemical constituents is observed. Additionally, increased salinity in upper reaches of Tampa Bay have been used as a metric for increased tidal flushing.

Circulation restriction zones are a side-effect of maintenance dredging in a shallow estuary. Circulation restrictions are described as shallow zones on the edges of deep, maintained zones, and are therefore heavily affected by irregular bottom topography in shallow, partially to well-mixed estuaries. These zones experience a decrease in lateral exchange with the adjacent deep channel, increasing local residence times for dissolved chemical constituents within the water column (Abdelrhman, 2005). The creation of deeper zones, caused by maintenance dredging of commercial ship channels, has the potential to increase the number of circulation restriction zones in a particular estuary (Goodwin, 1987).

### *2.8 The Providence River and Harbor Dredged Material Management Plan*

Dredging has occurred in the Providence River since 1853. Over 150 years of dredging projects have resulted in 43.2 million cubic meters of material removed from the bottom of Narragansett Bay (USACE, 2002). The Providence River Ship Channel is the main passageway through Narragansett Bay into the Port of Providence, and is maintained from Fox Point in Providence, South to the east passage off of Prudence Island. The channel is separated into 5 reaches for the purpose of management: Fox Point Reach, Fuller Rock Reach, Sabin Point Reach, Conimicut Point Reach, and Rumstick Neck Reach. The official controlling depth, or shallowest depth in the established channel at MLLW (mean lower-low water), is 40 feet, or 12.2 meters. Based on hydrographic surveys taken from 1977 to 1999, the overall Shoaling rate of

the Providence River Ship Channel was determined to be roughly 108,000 cubic meters of material per year. The fastest rates occur in the upper Reaches of Fox Point, Sabin Point, and Fuller Rock, where the Shoaling rate typically exceeds 10 cm of deposition per year (USACE, 2002, 2005). Shoaling rates diminish downstream of the head of Narragansett Bay as bed material increases in grain size. Commerce into the Port of Providence consists of mostly liquid petroleum products, with smaller amounts of salt, cement, steel, and asphalt being shipped up the Bay (USACE, 2002). Failure to provide inadequate depths for steadily-increasing drafts of vessels that ship these materials was determined detrimental to the State of Rhode Island's commercial efforts.

Dredging for the previous Providence River and Harbor Dredging Project (PRHDP) began in April 2003 and ended in July of 2005. Due to heavy Shoaling in the Ship Channel, the US Coast Guard placed restrictions on vessels traveling up Narragansett Bay to maximum drafts of 10.6 meters and one-way traffic of larger vessels, requiring vessels to wait for passage in lower parts of the Bay. Before 2003, the last dredging project was completed in 1976. In the 2003 PRHDP, 0.9 million cubic meters of dredged material that was determined unsuitable for offshore disposal was placed into Confined Aquatic Disposal (CAD) cells, strategically placed into the footprint of the Providence River Ship Channel immediately to the south of the Fox Point Hurricane Barrier (USACE, 2005). The deepest of these cells was 28 meters below the river floor. 1.5 million cubic meters of additional material was dredged in order to create these CAD cells. This material, below a certain depth, was determine

suitable for offshore disposal. Unsuitable material was placed into the CAD Cells (USACE, 2005).

The current dredging project is scheduled to begin in late 2019 to early 2020. It is estimated that a similar amount of material will need to be removed from the Providence River and Harbor area. For the upcoming PRHDMMP, Edgewood Shoals is being considered for the placement of a CAD cell, due to the Shoal's proximity to the Ship Channel, and a lack of viable space in the footprint of the Ship Channel for additional CAD cells. This project requires the building of additional channels to be used for access to and from the Cell. If USACE is planning a dredging project on Edgewood Shoals for the placement of a CAD Cell, our hypothesis is that there is a specific bathymetric modification that can be applied to the Shoal which may induce flushing and exchange. Working with USACE to design a series of scenarios, I propose a series of bathymetric alternatives that may prove to be environmentally beneficial to Edgewood Shoals.

### 3. METHODS

This project involves the integration of the 2005 ADCP data and the 2010 Tilt Current Meter data to identify key circulation patterns on Edgewood Shoals. Then, the Regional Ocean Modeling System (ROMS), a finite-difference numerical model, is run using environmental forcing from Summer 2010 and is used as a reference test to ensure that these key circulation patterns are accurately represented. Finally, using the validated numerical model, I can then alter the bathymetry on Edgewood Shoals to test a suite of dredging scenarios, and analyze the key changes to the circulation pattern based on the bathymetric alterations.

ROMS (Shchepetkin and McWilliams 2003, 2005) is a 3-dimensional, terrain-following, free-surface numerical model that solves the Reynolds-averaged Navier-Stokes equations (RANS), as well as the equations for the conservation of energy and scalars using simplifying assumptions (Haidvogel et al. 2008, Shchepetkin and McWilliams, 2003). The model uses a curvilinear, Arakawa-C grid structure (Arakawa and Lamb, 1977) for the step-wise solutions to the RANS and conservation equations. Curvilinear grid structure enables the horizontal resolution to concentrate in specific areas, in this case the Providence River Estuary. Horizontal coordinates used in this model are cartesian, with vertically-stretched sigma coordinates in the vertical direction.

The Narragansett Bay ROMS (NB-ROMS) model has evolved through several efforts to improve and modify the model to properly simulate the hydrodynamics of Narragansett Bay. Improvement stages were run, coupled with targeted, real-time observational data sets consisting of current velocity profiles and hydrographic

properties such as salinity and temperature. There have been three generations of ROMS models, modified to specifically apply to the hydrodynamics of Narragansett Bay (Rogers 2008; Lasota 2009; Kincaid 2012). The first edition of the model was designed to only exhibit the processes of the upper bay (Rogers, 2008). However, it was determined that this version of the model had a domain boundary that was too close to the area of study, impacting the results in a negative way. The second generation of the Narragansett Bay hydrodynamic model used the ROMS source code again, and increased the model domain by extending the southern boundary to the northern edge of Rhode Island Sound (Lasota, 2009). Nevertheless, it was determined that the grid resolution ( $>130$  m) in the Providence River was too coarse to properly represent chemical and biological transport. The current version of NB-ROMS is known as the Full-Bay ROMS model, and has increased the grid resolution of the Providence River to  $<40$ m (Kincaid, 2012). The model domain was extended in the most recent version to include a southern boundary that extends into the mouth of Narragansett Bay to ensure that the study area will not be affected by the boundary location (figure 7). The model consists of 15 sigma layers in the vertical, and less than 40-meter grid resolution in parts of the Providence River in the horizontal. The Full Bay NB-ROMS model is the version that will be used for this project.

It was determined that the first and second generations of the NB-ROMS model did not perform when it came to properly simulating residual flows. Residual, or subtidal flows are instrumental in numerically describing long-term chemical and biological transport in the Bay (Kincaid, 2012). For this reason, this current study using the Full-Bay version of NB-ROMS is validated against both residual and



instantaneous tidal flows from ADCP (Bergondo and Kincaid, 2005) and TCM (Balt, 2010; Medley and Kincaid 2018, unpublished (see appendix B)) observational data collected on Edgewood Shoals.

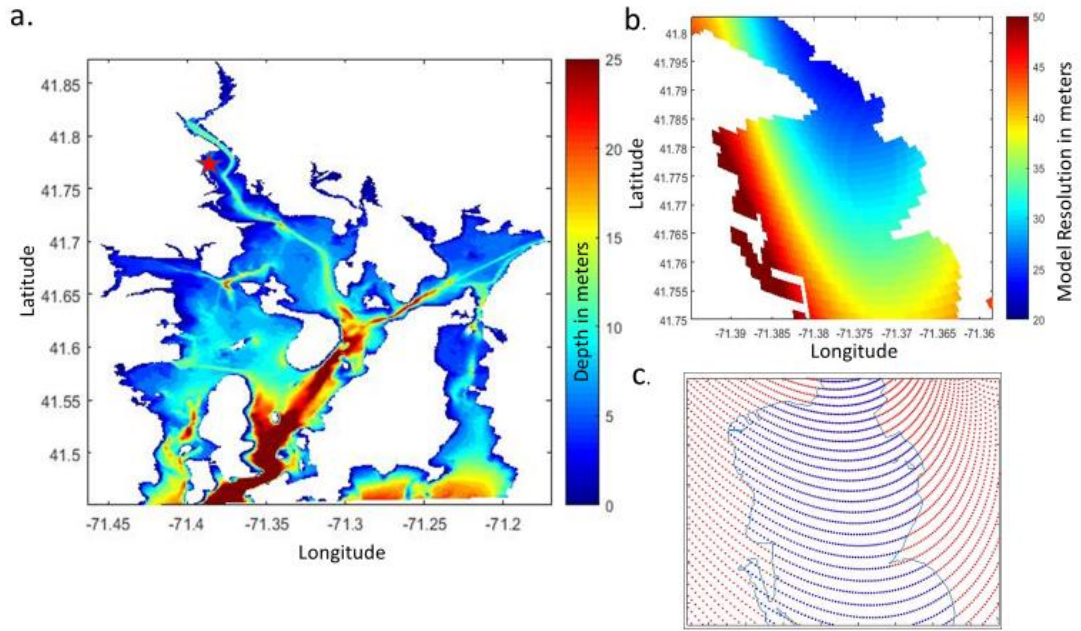


Figure 7: (a.) NB-ROMS Model Domain: The NB-ROMS Model domain, with Edgewood Shoals marked with a red star. The southern boundary consists of the mouth of Narragansett Bay at the Sakonnet River, East Passage and West Passage. The highest grid resolution is in the Providence and Seekonk Rivers to the north, and the lowest resolution is in Mount Hope Bay to the east. All boundaries are closed except for the southern boundary. (b.) A color contour plot of model resolution, in meters, on Edgewood Shoals. (c.) Grid nodes (blue = water, red = land) from the ROMS grid plotted on the outline of the Edgewood Shoals coastline.

### 3.2 Numerical Model Forcing:

This section includes the development of all ROMS model initial condition files, boundary forcing files, atmospheric forcing files, and most notably for this project, new grid files containing altered bathymetry for each dredging scenario. The

NB-ROMS model is forced by freshwater point sources (rivers), seven tidal harmonic constituents (M2, M4, M6, S2, N2, O1, K1) and surface atmospheric forcing fields. Alterations to the Narragansett Bay grid were performed in Matlab and the new files were saved to netCDF format.

The numerical model is forced by freshwater inputs from the USGS discharge gauges at the following rivers and WWTF's: Blackstone, Palmer, Moshassock, Seekonk, Pawtuxet, Taunton, Hunt, Green, Harding Brook, Muskerchug, Woonasquatucket and 10-Mile rivers, and the Fields Point, Bucklin Point and East Providence WWTF's. A correction factor is applied to account for groundwater discharge rates throughout the basin (Rogers, 2008). Figure 8 shows the river transport for four local rivers to Edgewood Shoals, the Blackstone, Moshassock, 10-mile and Pawtuxet Rivers. There are four discharge events throughout the 40-day model run occurring on decimal day 192, 196, 204.5 and 216. Winds are applied uniformly at the surface of the entire grid, using data for 2010 collected at T.F. Green Airport in Warwick, RI (figure 9 a,b). Atmospheric forcing parameters for the summer of 2010, namely long-wave and short-wave radiation, relative humidity, air temperature and pressure and precipitation are applied at the surface in a bulk forcing format.

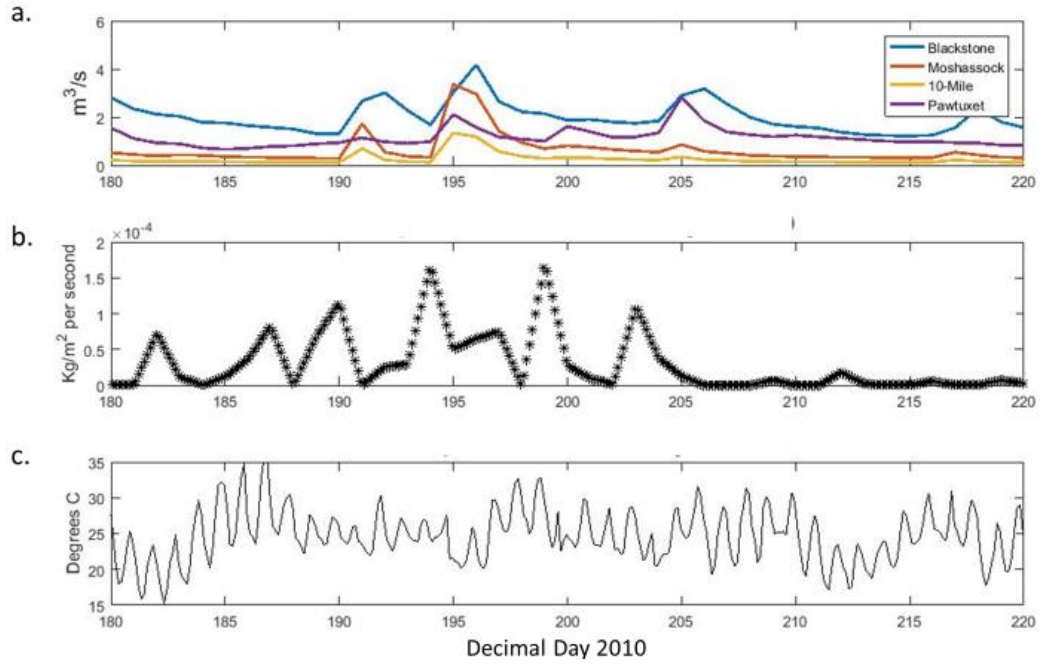


Figure 8. (a.) River transport observational data (USGS) used to force the numerical model during the modeling time period from decimal day 180-220 (June 30<sup>th</sup> – August 8<sup>th</sup>). River transport is indicated in cubic meters/second. (b.) Precipitation rate re-analysis data from the US Navy’s Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) applied as part of a bulk formula to force the model. Precipitation rate is in kg/square meter per second (c.) Air temperature in °C collected from T.F.Green Airport in Warwick, RI and applied as part of a bulk formulae to force the model.

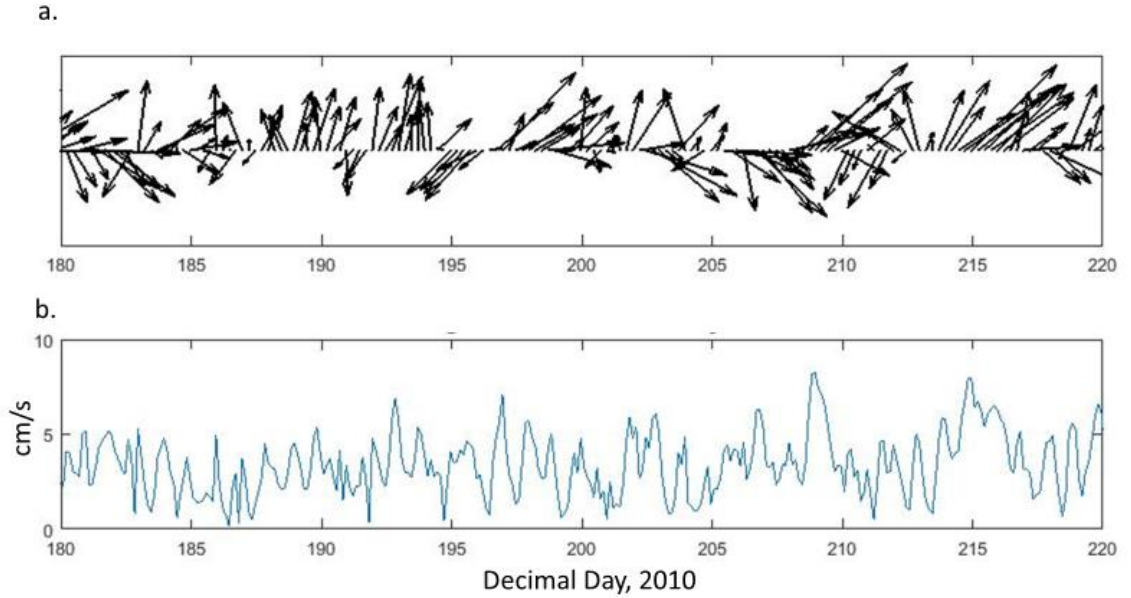


Figure 9: (a.) Observed wind direction with magnitude and (b.) wind magnitude from T.F. Green Airport in Warwick, RI used to force the numerical model during the modeling time period from decimal day 180-220 (June 30<sup>th</sup> – August 8<sup>th</sup>). Wind magnitude is in cm/s.

### 3.3 Model Boundary Conditions:

Boundary conditions are set as follows: the only open boundary is to the south, with closed conditions to the north, east, and west. The boundary condition for free-surface velocity uses the Chapman (1985) method. The 2-dimensional U- and V-momentum components are applied at the boundary using the Flather (1976) method. The 3-dimensional U- and V-momentum components and mixing turbulent kinetic energy are applied at the boundary using the Radiation method. Temperature and salinity are applied at the open boundary using a Radiation method with nudging, which allows water to leave the domain as well as enter at the boundary based on hydrographic data collected at the mouth of Narragansett Bay. Radiation with nudging has been proven effective in active/passive radiation conditions (Haidvogel et al, 2008). Nested at the open boundary at the mouth of the East Passage, West

Passage and Sakonnet River are values for water velocity, temperature and salinity that have been calculated from the Rhode Island Sound ROMS model (ROMS-RIS). ROMS-RIS is forced at its open boundaries from the ROMS-ESPRESSO model for the Middle Atlantic Bight. Tides are interpreted as water levels at the open boundaries, using tidal harmonics from the Advanced Circulation Model for Oceanic, Coastal and Estuarine Waters (ADCIRC) for the East Coast of the United States.

### *3.4 Initial conditions:*

Initial conditions are obtained from a ROMS re-start file containing existing gridded conditions for Summer 2010 with an additional 3-day spin-up period to obtain realistic density stratification. The model was spun-up from decimal day 180 to decimal day 183, and re-started on decimal day 180, with a barotropic time-step of 20 seconds and a baroclinic time-step of 10 seconds. The boundary file was checked to ensure that water levels at the east passage boundary follow closely to those of NOAA PORTS in Newport, RI. Experimental runs were completed for 40 modeled days, starting on decimal-day 180 and ending on decimal day 220.

### *3.5 Grid Generation:*

The alterations made to the NB-ROMS existing model for this project are as follows: alteration of bathymetry files to create nine bathymetric alternatives, or dredging scenarios, the addition of environmental forcing files using real-time data from Summer, 2010, and the addition of station files to receive data output from a series of locations in Edgewood Shoals.

The NB-ROMS grid is a 175 (East-West) by 350 (North-South) node curvilinear grid with 15 terrain-following sigma layers in the vertical. The grid

includes all of Narragansett Bay with the boundary set at the mouths of the East Passage, the West Passage and the Sakonnet River in a roughly east-west orientation. This boundary was determined to be far enough South in Narragansett Bay as to not affect the study area. The new bathymetric grid files were created using a MATLAB script that allowed the user to make changes to the already-existing grid file by creating and loading a series of depth planes to interpolate onto the existing grid. Each plane was created by a given a series of end-points (latitude, longitude, and point depth) that corresponded with points on the existing grid and determined the boundary of the plane. The depths within the boundaries of the plane are then interpolated linearly onto the existing grid based on the depths at the end-points. The complexity of the shape of the channel was determined by the overlapping of multiple interpolation planes of different depth values. Once the new depths had been interpolated onto the existing grid, the grid was smoothed using LP Bathymetry (Sikirić et al., 2009), using the linear programming capabilities of LP\_Solve (Berkelaar et al., 2005) to smooth.

Bathymetry in the 175x350 NB-ROMS grid used in this project comes from two sources. For modeling purposes in the Providence River, care was taken to use the most recent subsurface map of the area. Bathymetry from a depth survey completed by the USACE in May of 2017, as well as NOAA Coastal Relief bathymetry was interpolated on to the existing bathymetric grid obtained from the National Geophysical Data Center in 2014 for the area north of Ohio Ledge. This new bathymetry was then selectively smoothed, to ensure that the depths of both the Port Edgewood Channel (PEC) and Providence River Ship channel were preserved to the

greatest extent possible while still maintaining model stability. Increased detail on the Shoal was obtained by the USACE (2017) survey.

### *3.6 Analysis:*

Numerical tracers in the form of Lagrangian drifters and numerical dyes were used in this study to “tag” parcels of water and monitor their movement over time. Numerical tracer concentration was analyzed in a designated box on Edgewood Shoal (figure 10), with boundaries set as 41.7858 to 41.7800 degrees latitude and -71.3824 to -71.3919 degrees longitude. This area was chosen based on data from Narragansett Bay Estuary Program indicating low dissolved oxygen levels in the Turning Basin region of Edgewood Shoals (NBEP, 2014).

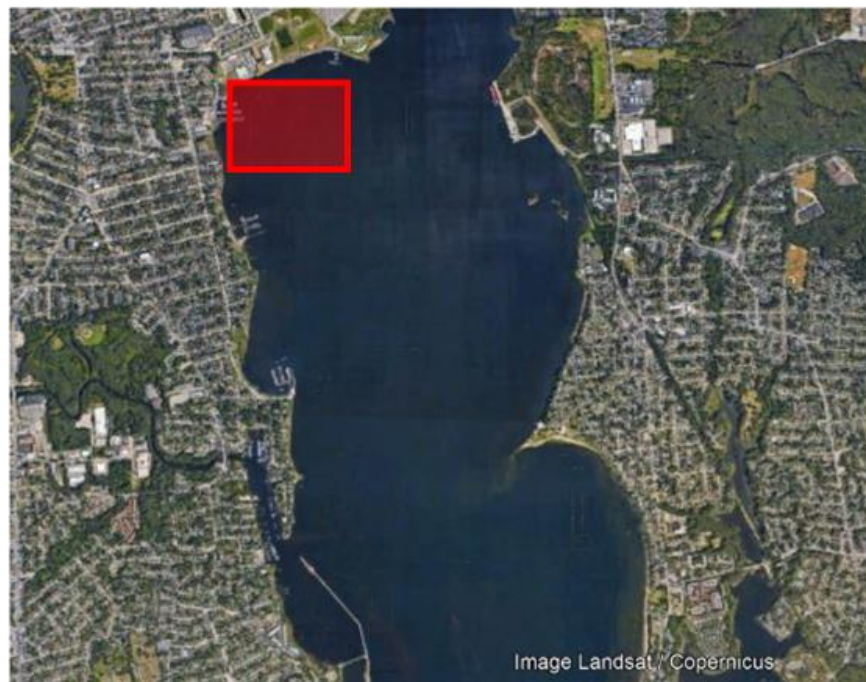


Figure 10: Pre-set area for analysis of numerical dye concentration and Lagrangian drifter counts on Edgewood Shoal. This pre-determined location was chosen based on the location of the Port Edgewood Turning Basin, which experiences chronic low dissolved oxygen during summer months (NBEP, 2014).

#### 4. RESULTS:

There are two accepted ways to use numerical models to gain insight into the flushing dynamics of a sub-estuary (Abdelrhman, 2005). The first is to monitor the movement of a numerical conservative tracer set at an initial concentration in the water column and tracked throughout the model run. The second is to simulate flow and transport to provide insight into natural flushing patterns on the both the tidal and subtidal scale. Both of these methods were used in this study to first explore the flushing pattern of Edgewood Shoal, and secondly to engineer a dredging scenario to enhance the natural effect.

##### *4.1 The Reference Case*

All differences between Dredging Scenario modeled cases will be described as differences from the Reference Case, which features the existing bathymetry on Edgewood Shoals, and the Providence River Ship Channel at a uniform controlling depth of 12 meters. The reference case used in this study is a 40-day modeled simulation of summer conditions for July and August, 2010. The minimum modeled air temperature during this time-period is 19°C and the maximum modeled air temperature during this time-period is 27° C (figure 8). The winds are predominantly from the south, between 2 and 4 m/s. A northwest (southeastward) wind event occurs between decimal day 180 and 182, reaching 4 m/s. Two stronger southerly (northward) wind events occur: The first being on decimal day 209, reaching a maximum of 8 m/s and on decimal day 214-216, reaching a maximum of 7 m/s (figure 9).



The Edgewood Shoals Turning Basin in the Reference Case is temperature and salinity stratified during the majority of the 40-day model run, with the exception of decimal day 215-217, where the water column is mixed by a southerly wind event of 8 cm/s. Temperatures in the Turning Basin surface water range between 24° C and 29° C and fluctuate diurnally (figure 11). The bottom water does not fluctuate diurnally, and ranges between 21 °C and 25° (figure 11b). Salinity fluctuates between 24 PSU and 28 PSU (bottom) and 19 PSU and 27 PSU (surface) (figure 11a). Overall, the surface water in the Turning Basin has a tendency to be fresher and warmer than the bottom water.

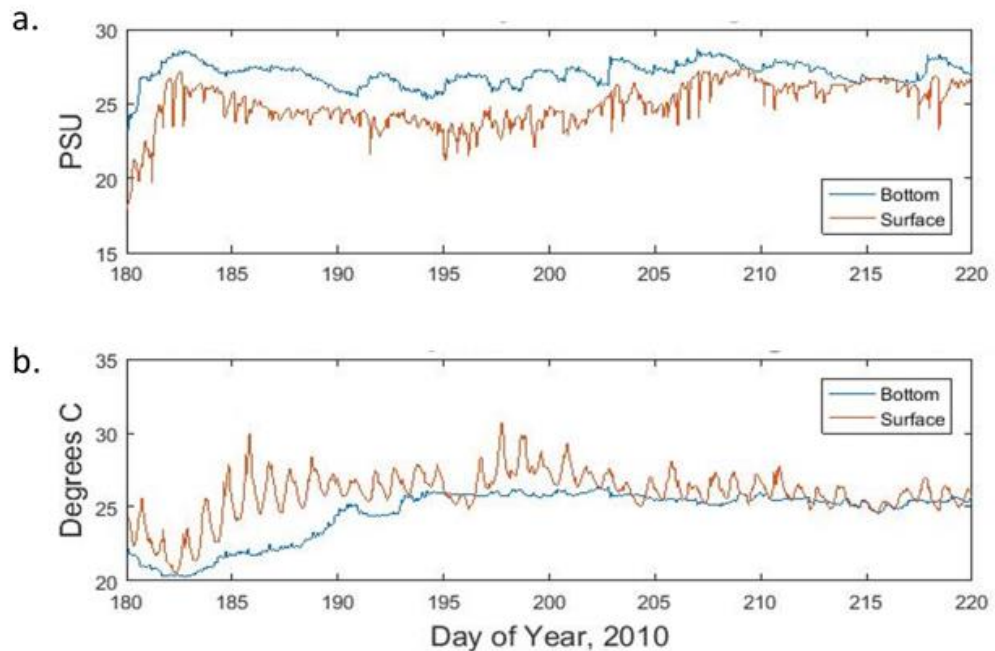


Figure 11: Modeled surface and bottom temperature (a.) and salinity (b.) in the Turning Basin on Edgewood Shoals, in °C and Practical Salinity Units, respectively. This figure indicates that the water column in the Edgewood Shoals Turning Basin is stratified throughout the model run, with the exception of decimal day 215-217, where the water column is mixed.

The Ship Channel in the Reference Case has a different temperature and salinity profile than the Turning Basin on Edgewood Shoals. The surface water has a temperature between 24° and 26° C (figure 12b) which is colder than the maximum surface water temperatures on Edgewood Shoals. The bottom water ranges in temperature between 19° and 21°, and fluctuates with the tides. Incoming tides feature cooler water in the bottom of the Ship Channel, while outgoing tides feature warmer water in the Ship Channel. This is consistent with the estuarine pattern of circulation, where cooler, saltier water is sourced from the lower part of the estuary and is advected up in the main channels in the bottom water.

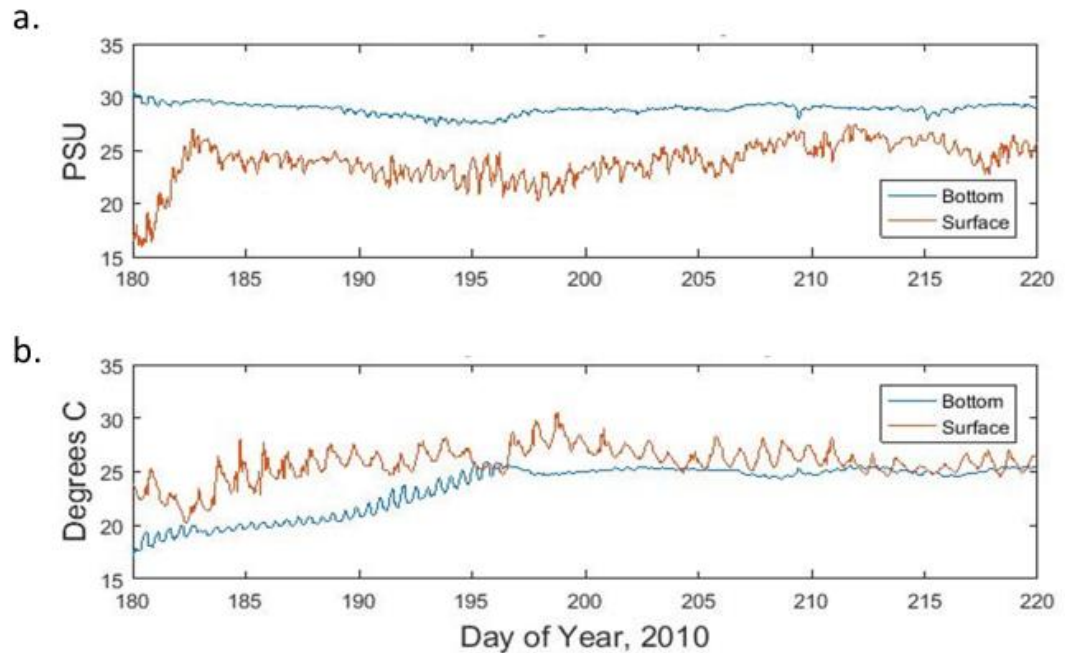


Figure 12: Modeled surface and bottom temperature (a.) and salinity (b.) in the Ship Channel adjacent to Edgewood Shoals, in °C and Practical Salinity Units, respectively. This figure indicates that the water column in the Ship Channel is stratified throughout the model run, with the exception of decimal day 212-215, where the water column is salinity stratified but not thermally stratified.

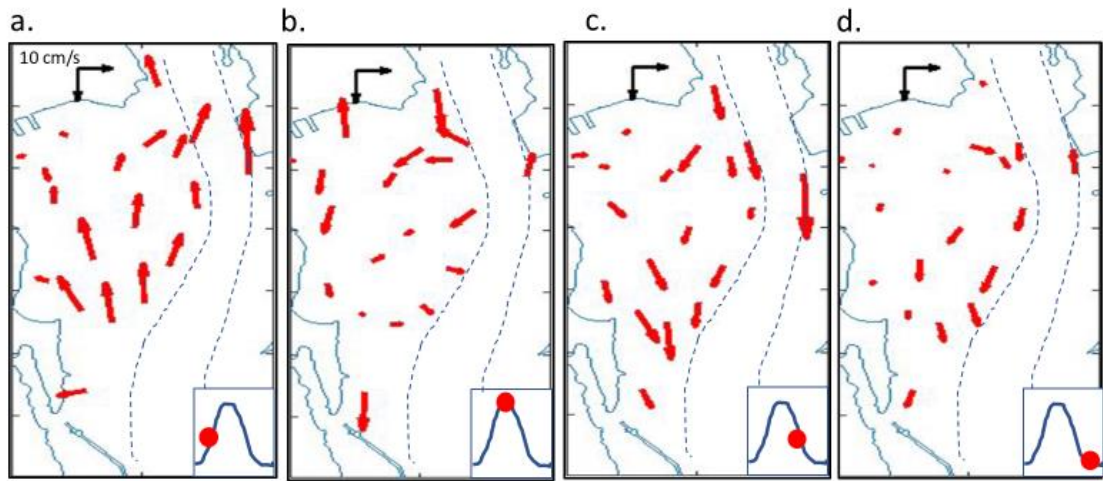


Figure 13: Modeled bottom water velocities on Edgewood Shoals during a neap tide. (a.) Instantaneous (tidal) flows on Edgewood Shoals and the adjacent ship channel during max flood (b.) at slack before ebb (c.) max ebb (d.) slack before flood. The dotted line marks the boundary of the Ship Channel.

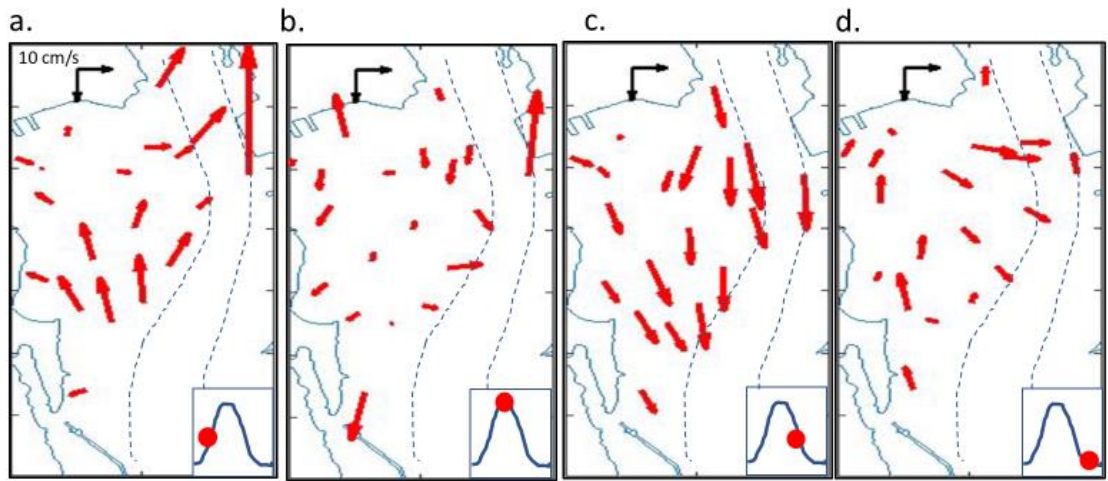


Figure 14: Modeled bottom water velocities during a spring tide. (a.) Instantaneous (tidal) flows on Edgewood Shoals and the adjacent ship channel during max flood (b.) at slack before ebb (c.) max ebb (d.) slack before flood. The dotted line marks the boundary of the Ship Channel. Note that during the flood, and slack before ebb, the value for velocities in the Ship Channel are three-times greater than the flows on the Shoal.

From the modeled velocities in ROMS, it is evident that a hydrodynamic disconnect exists between the flows in the Ship Channel and the Shoal. The model was run during a neap tide cycle, (tidal range of 0.8 meters), a spring tide cycle (tidal range of 1.2 meters), and a mixed cycle (tidal range of 0.9 meters). Tidal, or instantaneous velocities in the bottom water of the Shoal span from  $<0.1$  m/s on the inner Shoal (Turning Basin), and generally increase with distance moving towards the shipping channel, with a slight increase in the deeper Port Edgewood Channel. During the max ebb and max flood (figures 13 and 14 frames a and c), the Ship Channel (boundaries marked by a blue dotted line) experiences velocities that are 3-4 times larger than the averaged Shoal velocities during the same point in the tidal cycle. During spring slack

before ebb (figure 14b), the Ship Channel is experiencing a relatively strong northward flood at 15 cm/s, while the Shoal velocities are weak and net-southward.

Numerical dyes are useful in showing patterns of flushing with materials that have diffusive properties. Figure 15 is the 3-day evolution of dye concentration in the Turning Basin on Edgewood Shoal during the strong neap cycle that occurred during the 40-day model run period. Using the e-folding curve as a reference to residence times of water on the Shoal, the Turning Basin bottom water reaches a state of fully “flushed” roughly 1.2 days after the release of the constituent.

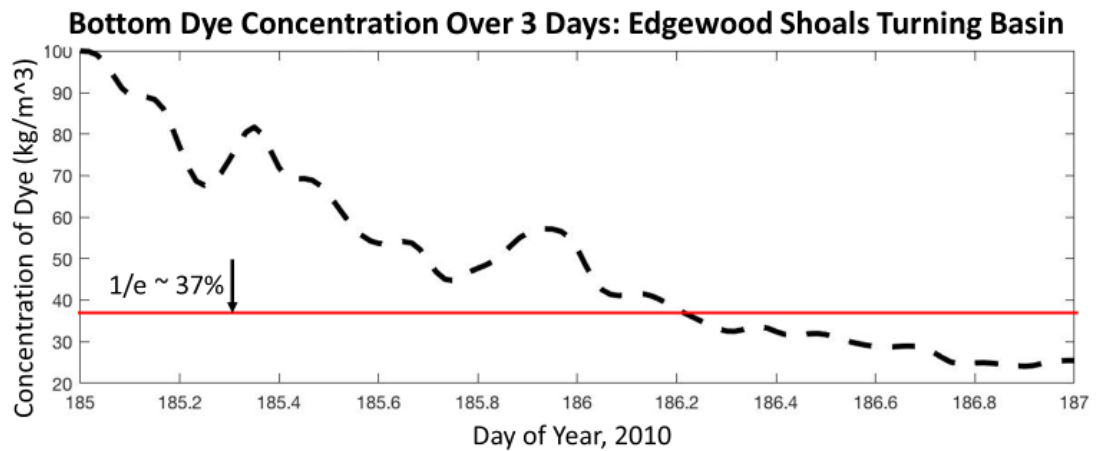


Figure 15: Time-series of dye concentration in the reference case. The red line marks the e-folding concentration, or 37% of the initial concentration, a method for determining whether a subregion is flushed.

According to model results, the Ship Channel and Edgewood Shoal experience two different surface elevation regimes depending on the stage of the tide. Faster flow that occurs in the Ship Channel at times causes the surface elevation in the Ship Channel to rise. Figure 16 shows an average of six surface elevation differences during a spring (red line) and neap (black line) tidal cycle. Over the 12-hour cycle, it is evident that a pattern emerges in the surface elevation difference between the Channel and the Shoal. As the Providence River “fills” during the tidal flood, the surface elevation difference between the Shoal and the Ship Channel decreases. During the slack before tidal flood, in the neap cycle, the Ship Channel sits roughly 0.5 cm higher than the Shoal.

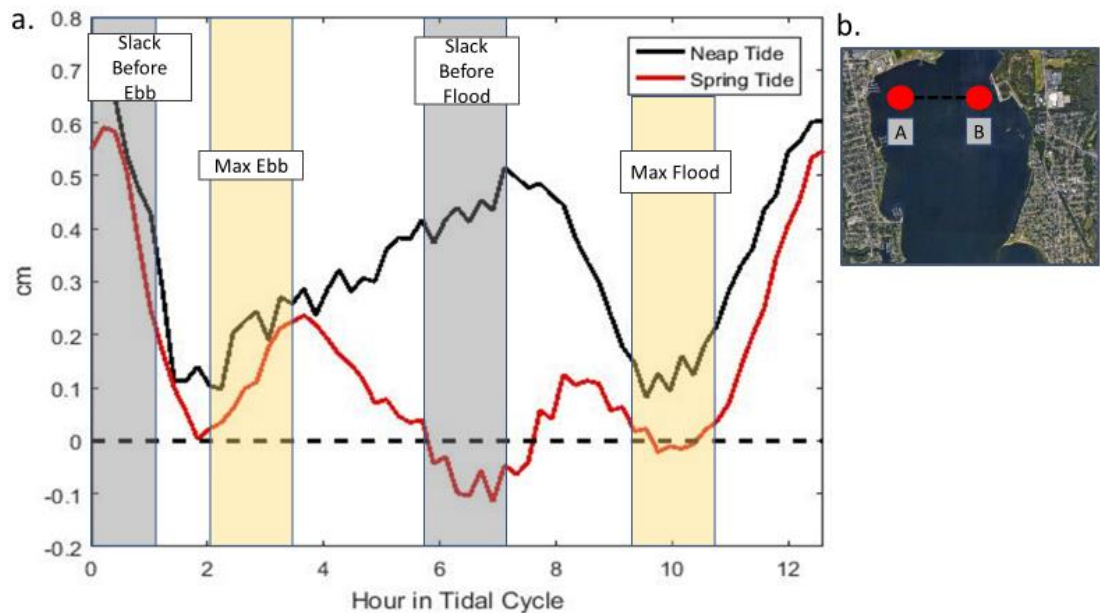


Figure 16: (a.) Modeled surface elevation difference between the Ship Channel and the Turning Basin on Edgewood Shoal over 6 averaged neap (black) and spring (red) tidal cycles. A negative value indicates that the Shoal surface elevation is higher than the Ship Channel, whereas a positive value indicates that the Ship Channel has a higher surface elevation than the Shoal. (b.) A and B represent the locations chosen for sea-surface elevation output. A represents the Shoal location whereas B represents the Ship Channel location. These locations for surface elevation output are also used in figures 27 and 28.

The reference case has a specific way of exchanging water with the Ship Channel. During the max flood (figure 17), the water moves eastward from the Turning Basin to the Ship Channel observed in flows moving towards the east, by way of a jet immediately south of Fields Point. This result is also visible in TCM observational data, (figures 5 and 6). From here, any water that reaches the Ship Channel is carried southward down-bay during the ebb. These same results were observed in the analog models of Edgewood Shoals that were completed by Australian National University researchers (Figure 4). During the slack before flood, there is a second pulse of water off of the Shoal, this time onto Edgewood Shoals (Figure 18) and southward down the Port Edgewood Channel. This feature is not observed in the analog models of Edgewood Shoals, due to the lack of a Port Edgewood Channel in the design of the tank. However, these westward (onto Shoal) and southward (down PEC) pulses are clearly visible in the moored ADCP, and TCM observations from 2005 and 2010, respectively.



### Early-Max Flood:

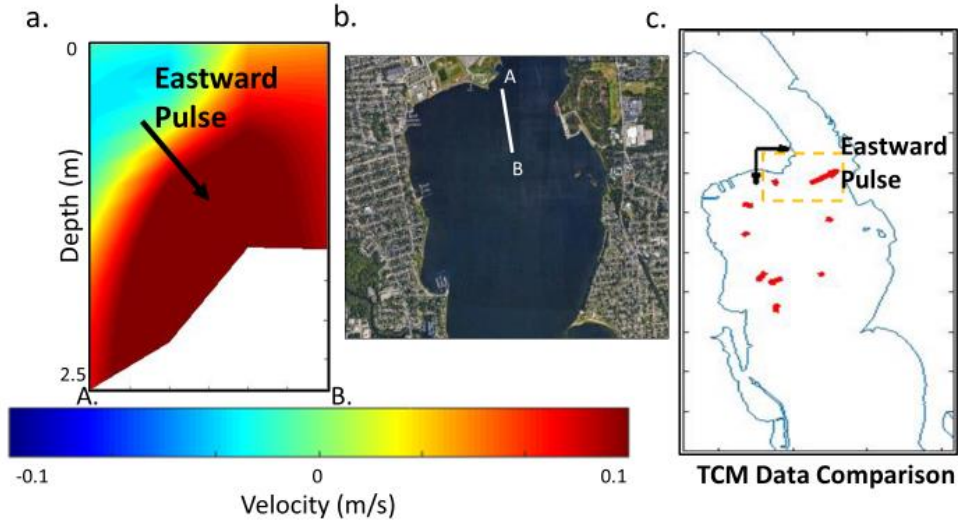


Figure 17: (a.) An interpolated transect of the modeled velocities occurring during an average of all max flood time-periods from the 40-day run. (b.) Location of the transect, with a red arrow signifying eastward flow and the blue arrow signifying westward flow. (c.) Averaged observational data of the flow pattern during the max flood.

### Slack Before Ebb :

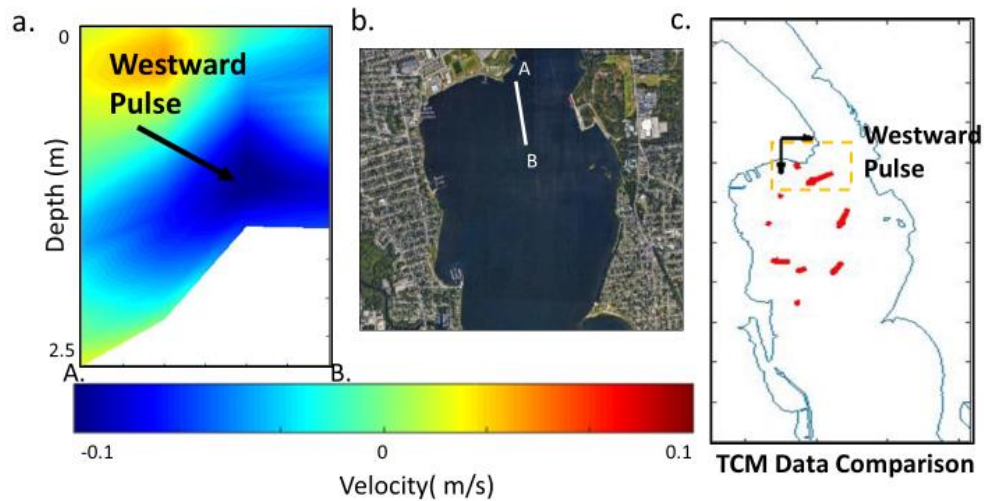


Figure 18: (a.) An interpolated transect of the modeled velocities occurring during an average of all slack before ebb time-periods from the 40-day run. (b.) Location of the transect, with a red arrow signifying eastward flow and the blue arrow signifying westward flow. (c.) Averaged observational data of the flow pattern during the slack before ebb.



While the Shoal in the numerical model has a repeatable pattern of tidal movement of water towards and into the Ship Channel, there are distinct Lagrangian tracers that remain on the Shoal over the course of multiple days. Figure 19 shows the positions of 5 individual Lagrangian drifters over the course of 4 days. After an initial release on day 185, during a neap tide, the drifters remain on the Shoal in the bottom water for four days past the release day, which is twice as long as the e-folding time for fully flushed Shoal, according to the model (see figure 15). The yellow drifter (Figure 19), completes a full clockwise gyre pattern before flushing off of the Shoal to the south of Fields Point.

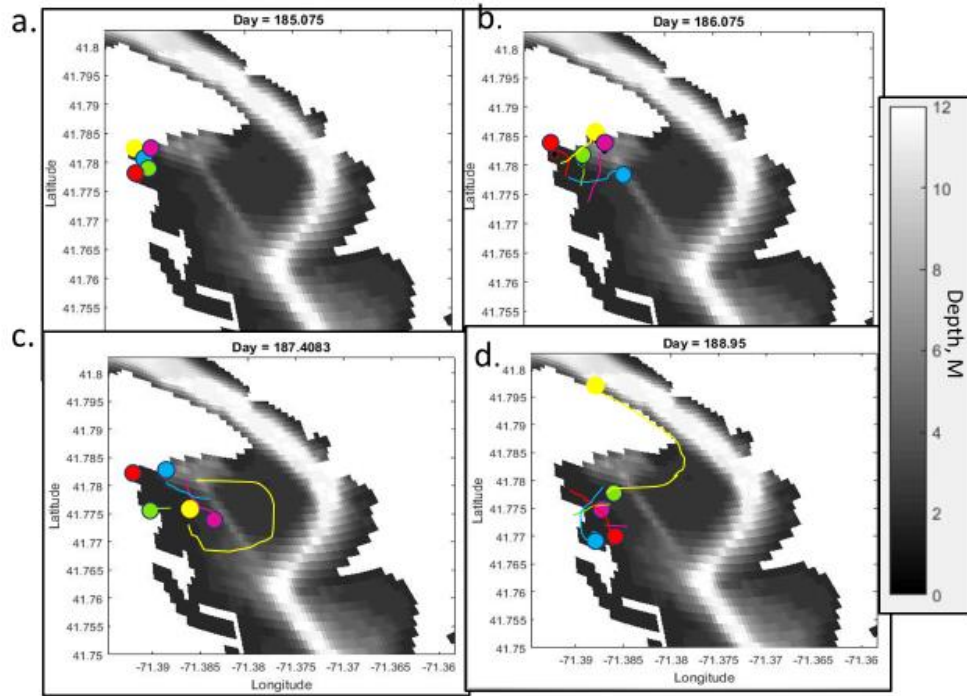


Figure 19: Locations and tracks of 5 Lagrangian drifters in snapshots at four different days post-release during the reference case model run. (a.) location of drifters on decimal day 185 (immediately after release) (b.) on decimal day 186, (c.) on decimal day 187 and (d.) on decimal day 188. The colored lines mark the path-lines of each drifter between frames. Note that the yellow drifter completes a full clock-wise path before exiting the Shoal to the south of Fields Point

#### *4.2 Results of Scenario Design:*

Confined Aquatic Disposal cells placed on Edgewood Shoals will need additional channels dredged from the Providence River Ship Channel to facilitate dredging/disposal equipment mobility. Locations for potential Cells, as well as access channels were determined based on a series of analyses for contamination depth (Michael Walsh, USACE, Pers. Comm 3/2018). The goal is a roughly 10,000 square meter (32 Acre) cell with a depth of 20-25 meters (65-81 feet). Issues with obtaining maximum preferred depth will be compensated with lateral surface area. Filling deeper areas with clean, subsurface material is encouraged in dredging scenario design. Any design that is deemed unsuitable to fit the needs of the USACE but provides maximum flushing benefit will be included in this analysis.

Bathymetric alternatives (“dredging scenarios”), were built in MATLAB by altering depths in the Edgewood Shoals region of the NB-ROMS grid. In this report, nine of the dredging scenarios will be introduced and hydrodynamic results from the ROMS model will be analyzed for each. The “Reference Case” in this report refers to the existing bathymetric features on the Shoal, referencing to depth soundings collected in May, 2017 (USACE, 2017).

Dredging scenarios were designed based on a prior knowledge of how the Shoal circulates. The analogue model of this system indicates that there is a persistent exit pathway for chemical constituents on Edgewood Shoals, by way of a hydrodynamic jet (Figure 4). This exit pathway at the top, northeast section of the Shoal is indicated by plumes of dye in the experiment that travel along the upper edge of the Shoal (immediately to the south of Fields Point), and are pushed into the Ship Channel, where they are then transported down-bay. The observation of this exit

pathway caused us to experiment with the augmentation of this conduit by dredging an east-west channel beneath the area of Fields Point as our dominant dredging design.

In the numerical model results for the Reference Case, there are two periods in each tidal cycle where there is a movement of water towards the edges of the Shoal: The slack before the ebb, where water pushes eastward from the Turning Basin to the Shoal-Channel interface just to the south of Fields Point, and max ebb, to slack before flood, where water flushes southward down the Port Edgewood Channel. Model runs 1a, 1b, and 1c highlight the first flushing pathway, by creating an access channel that connects the Turning Basin to the Ship Channel in an east-west oriented, 6-meter deep depression in the bathymetry. Run 2d is a sub-set of this design, creating channel with the same orientation and depth that does not connect to the Turning Basin. Scenarios 1b, and 1d highlight the second flushing pathway, by deepening the existing Port Edgewood Channel by an additional 3 meters. Due to the nature of the project being a design report for USACE, Runs 2b, 2c and 1c feature a modeled CAD cell, or a slight depression in the southwest section of the Shoal.

Additional scenarios were created in order to test physical characteristics of the existing Shoal circulation. Run 3a tests buoyancy-induced flows by creating a gradual, linear slope from the 2-meter Shoal center to the 12-meter Ship Channel. If the water retained on Edgewood Shoals is high in salinity, the grade in the slope at the Shoal-channel interface will encourage sinking water to flow west to east to meet the bottom water of the Ship Channel. Runs 2a, 2c and 1c fill in the Edgewood Shoals Turning Basin to the ambient depth of the Shoal (2 meters). These filling scenarios are environmentally and economically conscious, and would provide a beneficial

opportunity for clean material disposal that would otherwise need to be transported to Rhode Island Sound for offshore disposal.

Table 1:

Strategy	Model Run	USACE Scenario	Fill (Turning Basin)	Deepen Port Edgewood Channel	Dredge E-W access channel	Grade shoal to Ship Channel Depth	Modeled CAD Cell/Minimal Dredging
Maximum Dredging	1a	1			✕		
	1b	2		✕	✕		
	1c	9	✕		✕		✕
	1d	5		✕			
Minimal Dredging	2a	8	✕				
	2b	6					✕
	2c	3	✕				✕
	2a	7					✕
Grade Shoal	3a	4				✕	

## DREDGING DESIGN I: Maximum Dredging

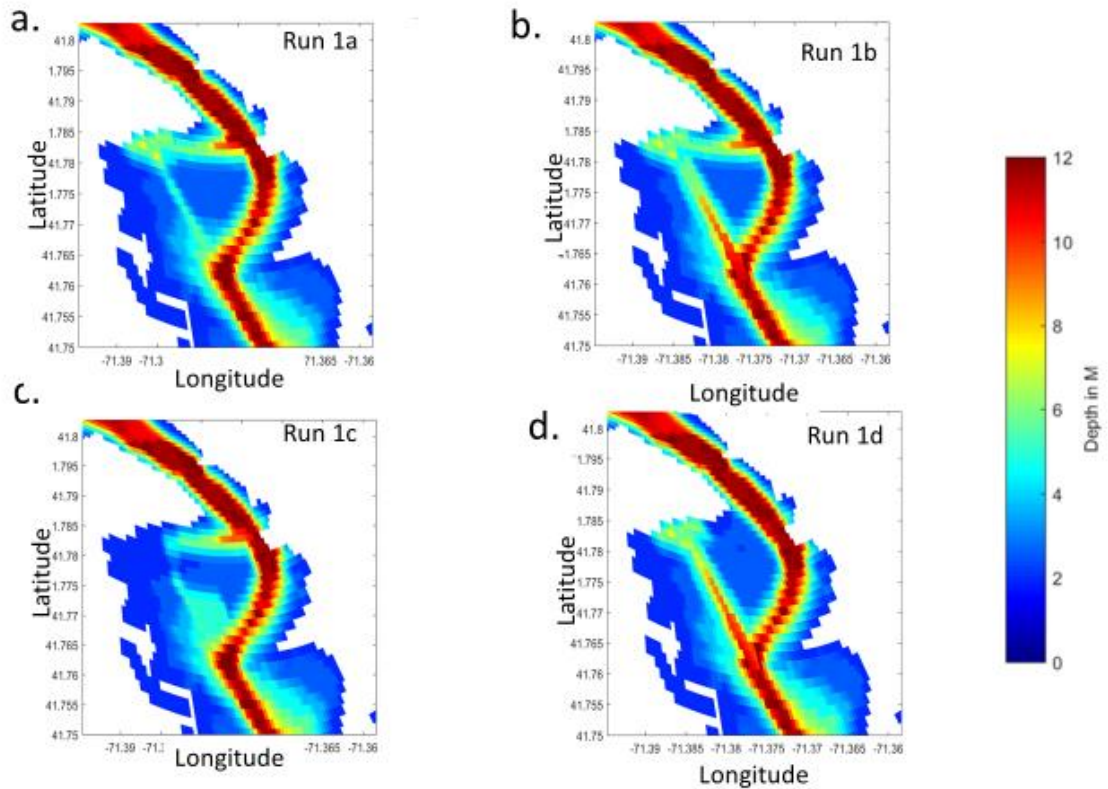


Figure 20: (a.) Dredging Run 1a map of depths. Run 1a deepens the northeast section of the Shoal by providing an east-west access channel. (b.) Dredging Run 1b map of depths. Run 1b deepens the northeast section of the Shoal by providing east-west access channel. Additionally, this scenario deepens the existing PEC by 2 meters. (c.) Dredging Run 1c map of depths. Run 1c fills in the Port Edgewood Turning Basin to an ambient depth of 2 meters, adds an east-west access channel, and adds a modeled CAD cell depression at the edge of the PEC. (d.) Dredging Run 1d map of depths. Run 1d deepens the existing PEC by an additional 2 meters.

## DREDGING DESIGN II: Minimal Dredging

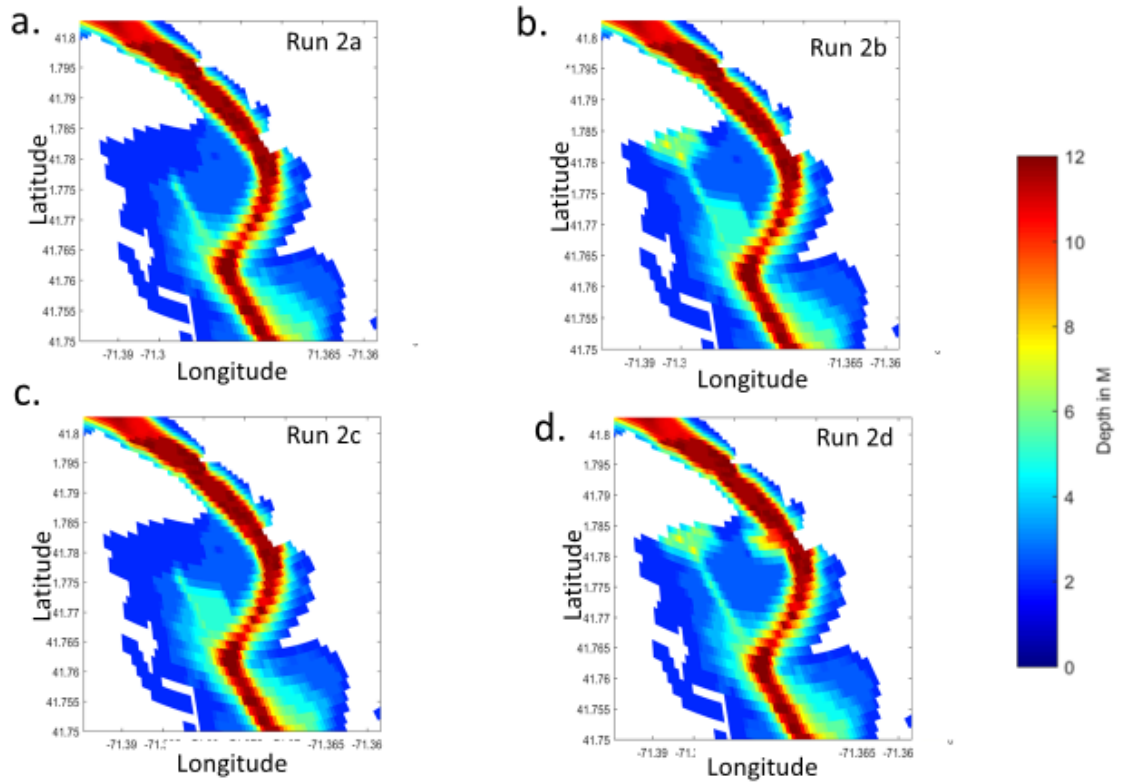


Figure 21: (a.) Dredging Run 2a map of depths. Run 2a fills in the Port Edgewood Turning Basin to an ambient depth of 2 meters. (b.) Dredging Run 2b map of depths. Run 2b adds a Modeled CAD Cell in the Southeast section of the Shoal. (c.) Dredging Run 2c map of depths. Run 2c adds a Modeled CAD Cell in the Southeast section of the Shoal, as well as fills in the Turning Basin to an ambient depth of 2 meters. (d.) Dredging Run 2d map of depths. Run 2d adds a short access channel in the eastern section of the Shoal.

### DREDGING DESIGN III: Enhance Buoyancy-Driven Flows

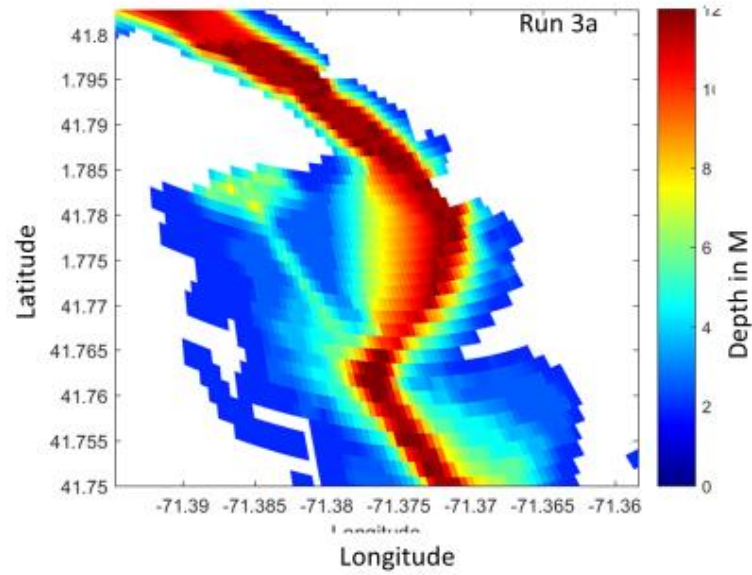


Figure 22: Dredging Run 3a map of depths. Run 3a grades the Shoal to the depth of the channel, shallowing the slope of the Shoal-Channel interface.

#### *4.3 Results of Model Runs of Dredged Scenarios*

Several lines of evidence, including repeat DO surveys, moored and spatial circulation data and lab circulation models, suggest Edgewood Shoals suffers from chronically poor water quality related to restricted flushing due to distinct hydrographic regimes created by dredging a deep channel adjacent to a shallow Shoal. I am using an existing hydrodynamic model combined with existing circulation data to further define specific details of circulation on and flushing from Edgewood Shoals. Modeling cases are also used to explore a number of strategic dredging scenarios for Edgewood Shoals, defined in consultation with USACE, and to characterize how these might lead to improved flushing and water quality. Eight experimental dredging scenarios will be compared in this section (Runs 1a, 1b, 1c, 1d, 2a, 2b, 2c, 2d). The majority of the results for Scenario 3a will be presented in Appendix C, as this was a test for buoyancy-driven flows and did not characterize a realistic dredging scenario.

Three days was the time-period chosen as a time window to monitor numerical dyes, because the dye concentration drops off significantly after 3 days and the results stabilize. Dye concentrations fluctuate due to tidal flows. Since surface water has greater tidal velocities than the bottom water, overall, the concentration of dyes in the surface water fluctuate at a greater frequency than concentrations of dye in the bottom water. The overall trend of dye is towards zero concentration, or completely flushed



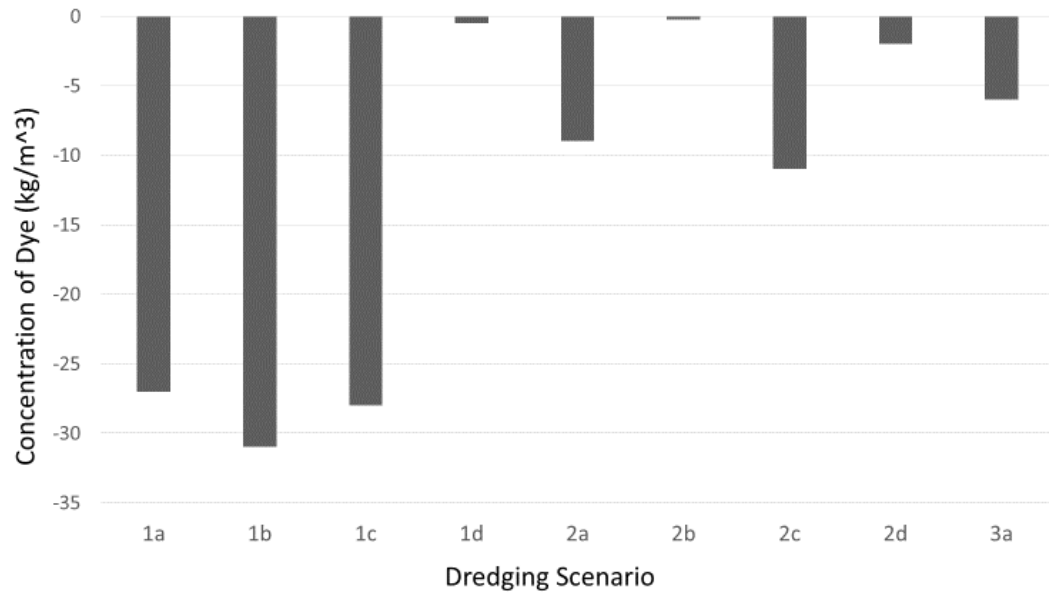


Figure 23: Difference in numerical dye concentration in the bottom water between the Reference Case and each subsequent Dredging Scenario, after 24 hours. The initial concentration of numerical dye in the analysis box is 100 kg/m<sup>3</sup>. Differences are in kg/m<sup>3</sup>, where a negative value indicates less dye on the Shoal than the Reference Case, and a positive value indicates a retention of dye on the Shoal in comparison to the Reference Case.

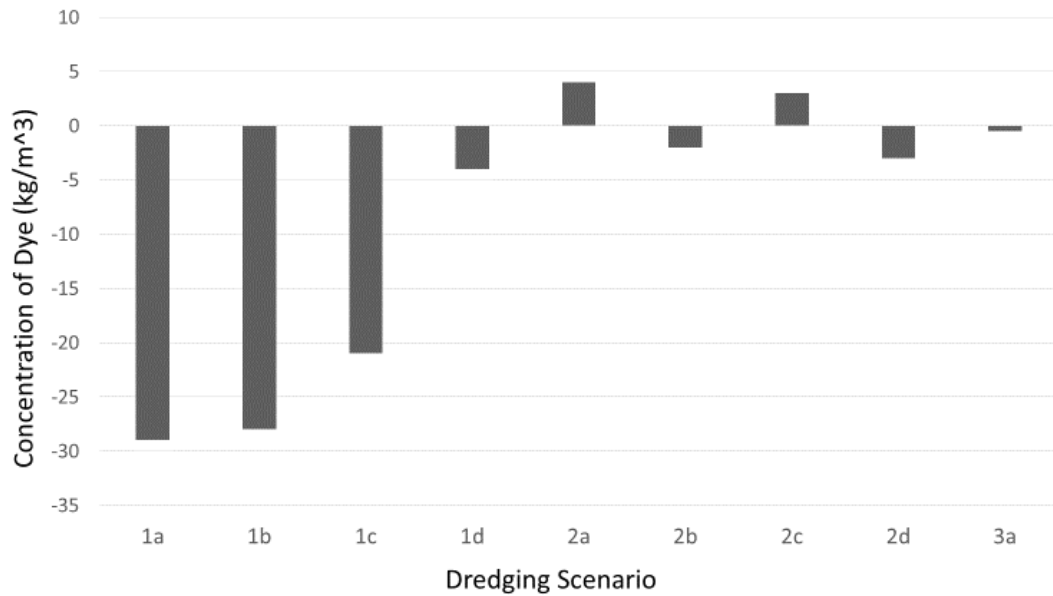


Figure 24: Difference in numerical dye concentration in the surface water between the Reference Case and each subsequent Dredging Scenario, after 24 hours. The initial concentration of numerical dye in the analysis box is  $100 \text{ kg/m}^3$ . Differences are in  $\text{kg/m}^3$ , where a negative value indicates less dye on the Shoal than the Reference Case, and a positive value indicates a retention of dye on the Shoal in comparison to the Reference Case.

After 24 hours of the model run, Runs 1a, 1b and 1c have 27%, 32% and 30% less dye in the bottom water of the Shoal than the Reference Case (figure 23). Runs 1d, 2b, 2d feature little to no difference between the dye concentration in the bottom water versus the Reference Case. Runs 2a and 2c have retained roughly 10% less dye in the bottom water of the Shoal than the Reference Case. In the surface water (figure 24), Runs 2a and 2c have a higher concentration of dye in the surface waters than in the surface water of the Reference Case after 24 hours. Similar to the bottom-water trend, 1a, 1b and 1c have retained between 25% and 30 % less numerical dye in the surface water than in the Reference Case.

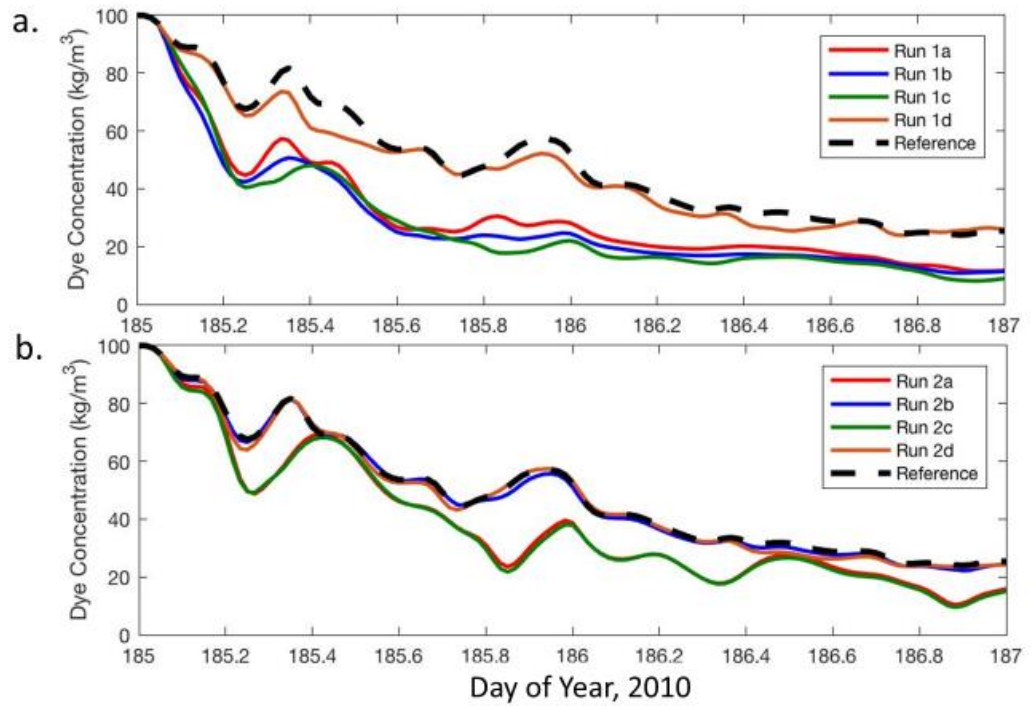


Figure 25: A time-series of numerical dye concentration in the bottom water of the analysis box on Edgewood Shoals during 3 days of the model run (Neap tide). Dye was released at  $100 \text{ kg/m}^3$  on the first timestep of decimal day 185. The black dashed line indicates the pattern of dye concentration evolution in the Reference Case.

Dyes that were released in the model were tracked over a series of 3 days following an initial release on decimal day 185. Figure 25 is a time-series of the bottom dye concentration of all scenarios, and the Reference Case. Figure 25 indicates that there is little difference in dye concentration evolution with time between the Reference Case, Runs 1d, 2b and 2d (figure 25a, 25b). The highest differences in dye concentration evolution with time occur with Runs 1a, 1b and 1c (figure 25a).

E-folding times (Monsen et al., 2002), an accepted way to describe efficiency in river or estuarine flushing (the time it takes for each scenario to reach 37% of its original concentration (100%)) are featured in table 2. The values for these e-folding

times are highest (indicating longest retention times) in the Reference Case, Runs 2b and 2d with values of 1.22, 1.21, 1.22 (days) respectively.

When scenarios are grouped with their respective Shoal modifications, it is evident that out of the “Dredging Northern Access Channel”, Runs 1a, 1b and 1c, have the greatest effect in lessening the amount of dye constituent that remains on the Shoal. In the scenarios that place a CAD cell in the southwestern section of the Shoal (1c, 2b, 2c) Run 1c has the lowest retention time. Run 1c, which also fills in the turning basin, has the lowest retention time for water parcels out of the scenarios that fill in the Turning Basin.

Table 2:

<b>Model Run</b>	<b>Description</b>	<b>Days it takes to reach 1/e (37%) Dyes</b>	<b>Days it takes to reach 1/e (37%) Drifters</b>
Reference Case	Existing Bathymetry	1.22	0.95
1a	Dredge E-W Access Channel	0.50	0.10
1b	Dredge E-W Access Channel, Deepen PEC	0.50	0.15
1c	Dredge E-W Access Channel, Modeled CAD Cell, Fill Turning Basin	0.55	0.20
1d	Deepen PEC	1.19	0.30
2a	Fill Turning Basin	0.73	1.00
2b	Modeled CAD Cell	1.21	0.97
2c	Fill Turning Basin, Modeled CAD	0.72	1.01
2d	Dredge Short E-W Channel	1.22	0.95
3a	Grade Shoal	0.95	0.92

At the start of each numerical simulation, nine-hundred and seventy-five near-bottom Lagrangian drifters were introduced to the flow fields on Edgewood Shoals. Figure 26 (a, b) are time-series plots of the number of drifters in the analysis box

(figure 10) in the northwestern section of the Shoal over the course of three days of model runs. Runs 1a, 1b, and are the most efficient at removing drifters from the Shoal. The least efficient scenarios at removing drifters from the Shoal are the Reference Case, Runs 2a, 2b, 2c, 2d and 3a. After day 187.5 (2.5 days after release) float concentrations stabilize to a low value, but do not reach zero over the 3-day time window.

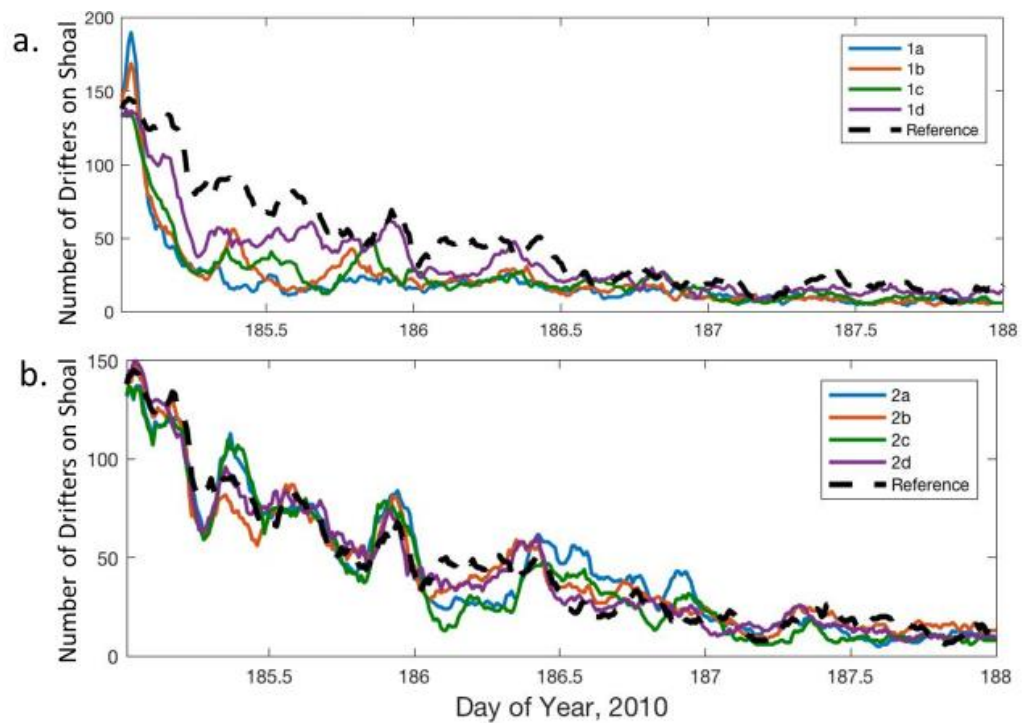


Figure 26: (a.) Total drifters on Edgewood Shoals over 3 Days during the neap tide for Experiment 1. Drifters were released at an incoming tide during the neap cycle (b.) Total drifters on Edgewood Shoals over 3 Days during the neap tide for Experiment 2. Drifters were released at an incoming tide during the neap cycle.

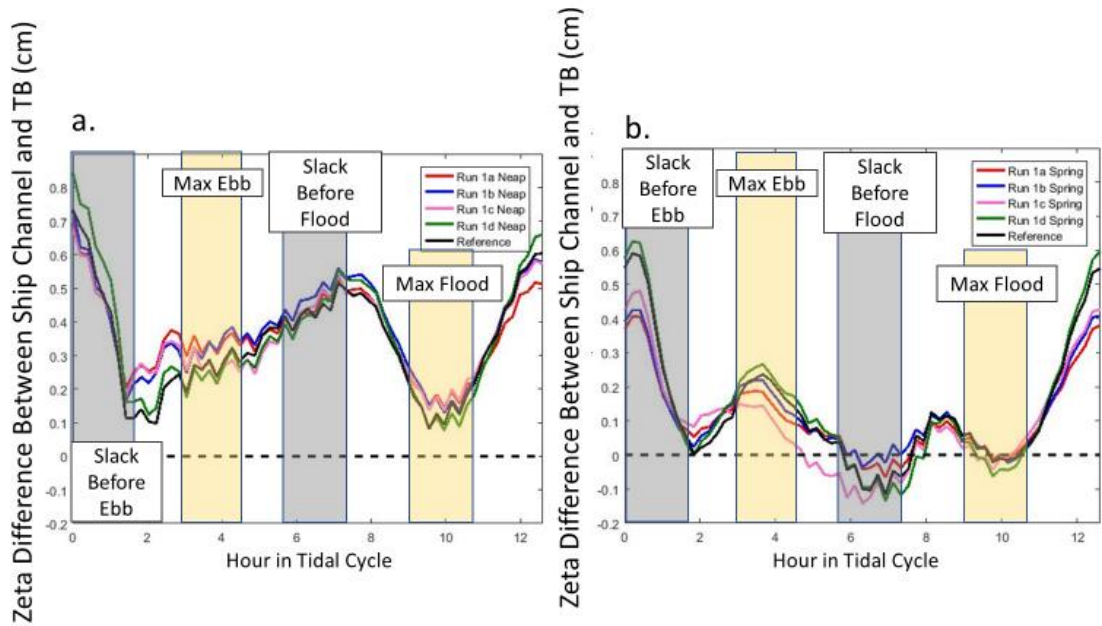


Figure 27: Modeled surface elevation (zeta) difference between the Ship Channel and the Turning Basin (TB) on Edgewood Shoal over 6 averaged neap and spring cycles, for each dredging scenario (Run 1a in red, 1b in blue 1c in pink and 1d in green). A negative value indicates that the Shoal surface elevation is higher than the Ship Channel, whereas a positive value indicates that the Ship Channel has a higher surface elevation than the Shoal.

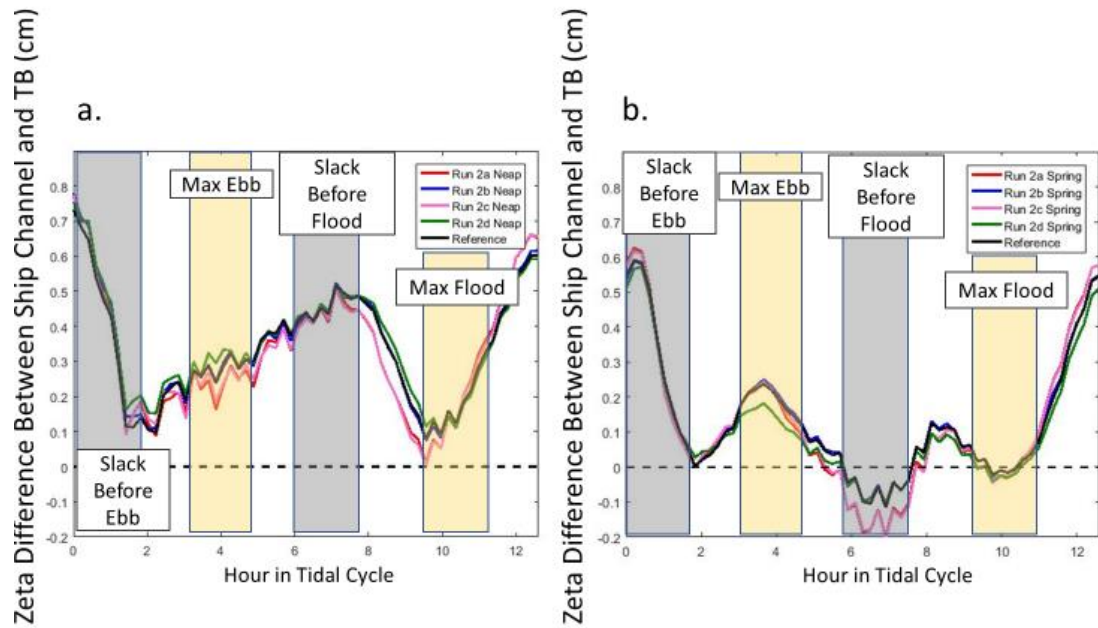


Figure 28: Modeled surface elevation (zeta) difference between the Ship Channel and the Turning Basin (TB) on Edgewood Shoal over 6 averaged neap and spring cycles, for each dredging scenario (Run 2a in red, 2b in blue 2c in pink and 2d in green). A negative value indicates that the Shoal surface elevation is higher than the Ship Channel, whereas a positive value indicates that the Ship Channel has a higher surface elevation than the Shoal.

Modeled differences in sea-surface height were calculated between the Turning Basin and the Ship Channel. From dredging design 1 (Runs 1a, 1b, 1c and 1d in figure 27) there is a roughly 0.1 cm increase in the difference between the reference case sea-surface height gradient, and the dredged cases during the neap tide. During the spring tide, the Shoal in run 1c sits higher, earlier in the tidal cycle than the reference case. This implies that a sea-surface height gradient is created between the Shoal and the Ship Channel that is greater than the reference case. This sea-surface height gradient leads to east-west flows that would move a constituent from the turning basin, off of the Shoal, which is consistent with both the drifter as well as numerical dye results. The same pattern occurs in the spring cycle in model runs 2a and 2c (figure 28), where

the Turning Basin (Shoal) sits higher than the adjacent ship channel, forming a sea-surface height gradient that produces off-Shoal flows.



## 5. DISCUSSION OF RESULTS

Results show that NB-ROMS is capable of reproducing key non-tidal characteristics of flow when compared with observational records. In comparisons of these residual flows, NB-ROMS captures the persistent clockwise gyre formation that is characteristic to the long-term circulation pattern on Edgewood Shoals. This gyre formation is understood to be the cause for the hydrodynamic disconnect occurring as a direct result of a steep bathymetric gradient between the Shoal and the adjacent Ship Channel. As a result of this hydrodynamic disconnect, bottom water residence times on Edgewood Shoals are higher than those of the Ship Channel, which has severe ecological impacts.

When considering circulation on a tidal scale, TCM observations suggest an important exchange pathway in the area directly to the south of Fields Point. There are two points in the tidal cycle that are determined from observations to be crucial to the east-west exchange flows onto and off of Edgewood Shoals. The two points of the cycle are the slack before ebb, and maximum flood. During the slack before ebb, every waterway to the north of Edgewood Shoals that is tidally influenced begins to empty between the relatively narrow ( $<0.5$  km) choke point between Fields Point (west) and East Providence (east). At this point in the tidal cycle, observations suggest that there is a relatively strong westward (Shoal-ward) pulse of bottom water of 8-12 cm/s (0.08 – 0.12 m/s) (figure 18). NB-ROMS captures this pulse in both magnitude and direction during the slack before ebb. During the maximum flood, the exchange flows reverse, and observations suggest an eastward (Ship Channel-ward) pulse of 10-15

cm/s (0.10-0.15 m/s) (figure 17). NB-ROMS captures these exchange flows during the max flood in both magnitude and direction.

While NB-ROMS captures the characteristic residual or non-tidal flows, as well as key parts of the tidal flow pattern which repeats itself every tidal cycle, the results from this Thesis determine that NB-ROMS consistently predicts numerical tracer removal at very high rates, three to five times faster than tracer removal from analogue models, and the residence times determined by the biochemical proxy of dissolved oxygen concentration. An explanation I present for this artificially fast numerical tracer flushing rate is that the numerical model cannot spatially resolve the exit pathway onto and off of the Shoal. This causes the material being removed from the Shoal to be flushed over a larger area, rather than through a narrow jet. A spatial resolution of 40 meters to resolve the physics of a 50-meter hydrodynamic jet is entirely unrealistic for this application, pictured in figure 29.

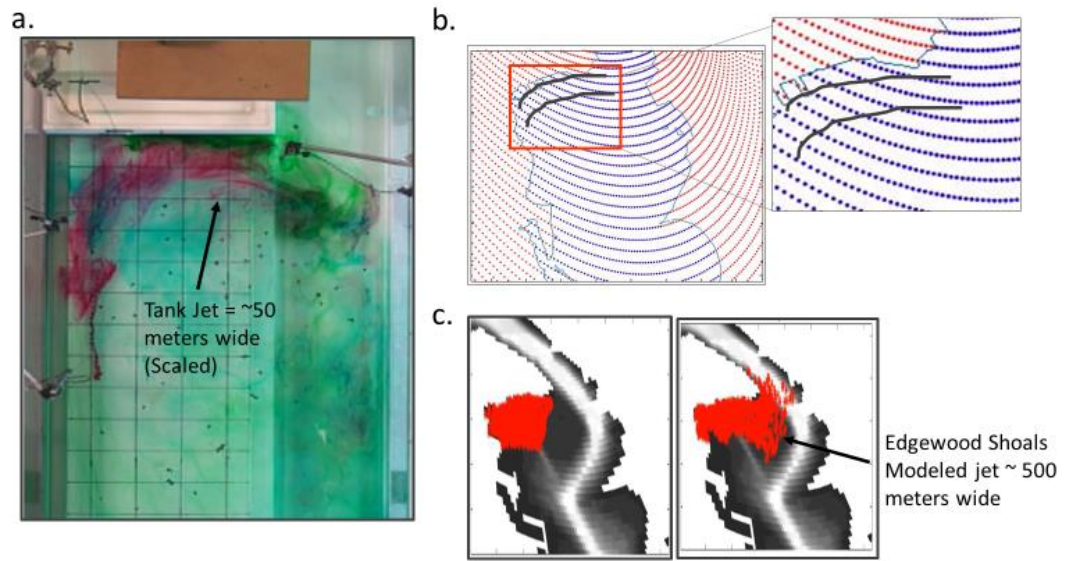


Figure 29: A spatial comparison of NB-ROMS horizontal grid resolution, alongside the analogue model hydrodynamic jet that makes up the northern section of Edgewood Shoals. (a.) Estimated width of jet from the ANU analogue model (figure 4). (b.) Model resolution, zoomed in to focus on an estimated outline of the hydrodynamic jet. (c.) A time-series image of the formation of the hydrodynamic jet in the numerical model. The modeled jet is 8-10 times wider than the jet formation that occurs in the analogue model.

A key outcome from this work is that inflow/outflow in the deep channel relative to the Shoal produces time-varying east-west sea surface elevation gradients that vary over the tide cycle and between spring-neap cycles. When waterways to the north of Edgewood Shoals that are tidally influenced begin to empty between the choke point between Fields Point and East Providence during the slack before ebb, the surface of the Ship Channel begins to sit high relative to the sea surface of the Shoal. This surface elevation gradient produces a westward pulse of water down-gradient onto the Shoal. During the maximum flood stage of the cycle, water from down-bay moves northward up the Port Edgewood Channel, and fills the Shoal. This water is then pulsed in an eastward (Channel-ward) jet off of the northeastern section of the Shoal

to the south of Fields Point. While NB-ROMS captures these time-varying sea-surface gradients, it still does not accurately depict the flushing of numerical tracers from this system.

The purpose of this project is to numerically simulate changes to the circulation on Edgewood Shoals resulting from a suite of bathymetric alterations. For this application, I argue that the NB-ROMS describes changes to the circulation patterns due to dredging with a reasonable level of confidence. While the Reference Case describes numerical tracer removal at a rate higher than what is expected in the natural system from a combination of biological proxies and observations, it can be taken as an experimental control. The assumption that needs to be understood is that all changes to the patterns of circulation in each experimental case are due to the bathymetric alteration alone. It is important to note these results and suggest alterations for future work to improve how a numerical model represents the circulation patterns on Edgewood Shoals. Nevertheless, I argue the improved flushing trends generated from my experimental cases are significant, optimal dredging strategies will indeed have a favorable environmental effect and should be implemented during the next maintenance dredging cycle of the Providence River.

One of the most impacted zones on Edgewood Shoals is the northwest section of the Shoal, or the area that makes up the Port Edgewood Turning Basin. This formerly maintained, 6-8-meter depression in the bathymetry is susceptible to extremely low dissolved oxygen counts in the summer, indicating bottom water that remains fairly stagnant. Observational studies have indicated that this area of the Shoal exhibits low tidal and residual flow during both spring and neap tide periods. In this study, one of

the important factors taken into account is choosing a dredging scenario that will allow the Turning Basin, or the northwest region of the Shoal, to increase instantaneous and residual velocities in order to flush this impacted region.

There is an understanding of estuarine flushing and water parcel residence times as being a function of the freshwater input rate from rivers, balanced by the outgoing flows in the lower estuary as it interacts with shelf-water (Asselin and Spaulding, 1993). Since this method does not take into account bathymetric structures that retain water, this formulation leads to relatively low residence times, and high estimated flushing rates. This is especially true in sub-regions of Narragansett Bay and the Providence River Estuary. In the case of Edgewood Shoals, applying this type of residence time calculation for the average Providence River water parcel is unrealistic, as it does not take into account the key circulation and flushing patterns that occur on the Shoal.

Numerical Dye results indicate that Runs 1a, 1b and 1c (east-west channel design) are the most efficient in removing dye from the Shoal than the reference case. Since exchange is classified in this area as the east-west flow of water onto and off of the Shoal, a significant increase in the eastward or westward velocities in the northwest section of the Shoal indicate that water is either moving eastward off of the Shoal into the Ship Channel, where it is transported down-bay, or that water is jumping the Shoal break and is making its way onto the Shoal in a westward motion. It is assumed that a northward-southward increase in velocities will not have this same effect due to the orientation of the Shoal in the vicinity of the Ship Channel.

Lagrangian drifter (float) results are an indicator of retention of water parcels in the analysis box, which is in the vicinity of the Port Edgewood Turning Basin on Edgewood Shoals. Scenarios 1a, 1b, 1c and 1d are the most efficient at removing drifters from the Shoal. These results indicate the importance of the first pathway for water to exit the Shoal, the east-west section just to the South of Fields Point. If an east-west channel is added to any dredging design, whether it be a CAD cell placement or Turning Basin filling, the residence times of water on the Shoal decrease by over 50%. Alternatively, if the second pathway for water exchange, the Port Edgewood Channel, is deepened, the results from the numerical dye analysis indicate relatively little decrease in the residence times of water indicated by dye removal. This result is perplexing, and may also be a result of struggling model resolution in the Port Edgewood Channel.

Temperature and salinity can be used as tracers of water masses comprising the Shoal and the Ship Channel. Surface water on Edgewood Shoals warmer and has a lower salinity than the surface water in the Ship Channel. When the Turning Basin is filled, the water column mixes. An increase in salinity coupled with a decrease in temperature is an indication of two different, but important processes. First, of the Ship Channel water mass moving onto Edgewood Shoals. Second, the water column in the Turning Basin mixing. Run 1d alters the temperature and salinity of the northwest section of the Shoal by decreasing bottom water temperature. Since Run 1d deepens the Port Edgewood Channel, it is evidence supporting the function of the Port Edgewood Channel as a conduit for saltier, cooler lower bay water onto and off-of the

Edgewood Shoals. The dredging of this channel is allowing cooler, saltier water in the form of Providence River Ship Channel bottom water to make its way onto the Shoal.

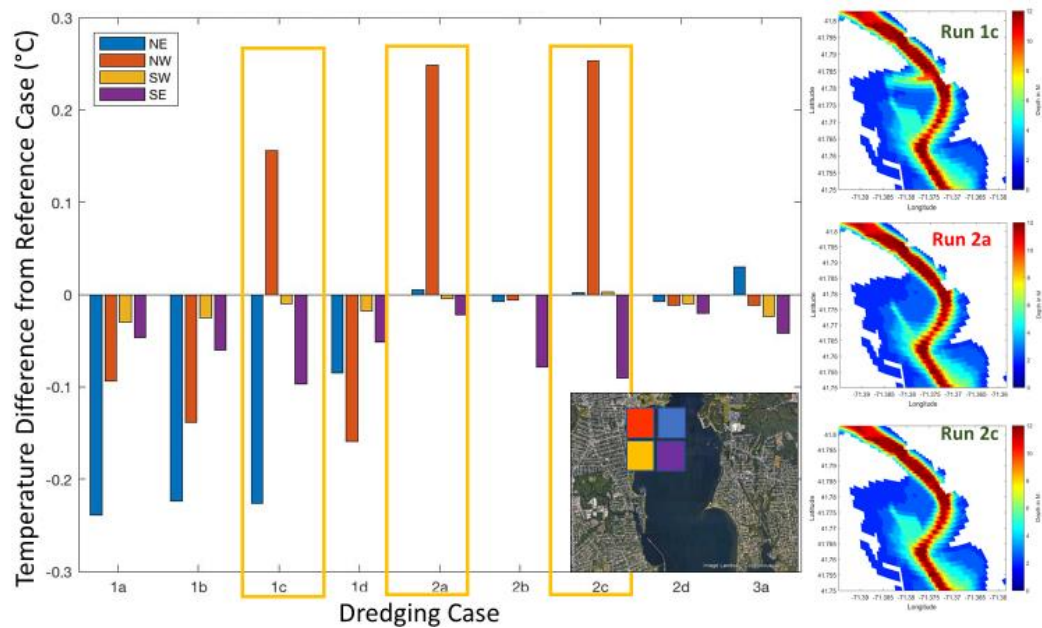


Figure 30: Graph of temperature difference between each model scenario run and the Reference Case, in °C. The inset satellite image with colored boxes represents the locations of each temperature difference bar. Each yellow box indicates model runs where the Turning Basin is filled.

If there are no outside sources, one way to increase temperature in the bottom water of a water column in a stratified water column during the summer months is to mix it. The temperature increase observed in the northwest section of the Shoal (in the vicinity of the Port Edgewood Turning Basin), is associated with filling in the Turning Basin to an ambient depth of 2 meters. This warmer water in comparison to the Reference Case, as well as horizontal velocities that are greater than those in the Reference Case, could indicate an increase in mixing of the water column (breakdown in stratification) associated with fill. Evidence pointing to this breakdown in

stratification indicated by warmer water (positive temperature difference) in the northwest section of the Shoal is seen in figure 30, where the entire water column above the filled Turning Basin has temperature and salinity characteristics of the surface mixed layer in the Reference Case.



## **6. CONCLUSIONS:**

The DMMP for the next maintenance dredging cycle of the Providence River and Harbor FNP includes the plan to construct a Confined Aquatic Disposal (CAD) Cell in a shallow area of the Providence River known as Edgewood Shoals. Environmental benefit for each dredging scenario is determined through analysis of flow structure on the Shoal, as well as the comparison of the retention of lagrangian drifters and numerical passive tracers (dyes) in the highly impacted section of the Shoal known as the Port Edgewood Turning Basin.

There are two major ways to decrease the residence times of water parcels on Edgewood Shoals. This is accomplished by enhancing the natural pathways that exist currently in order to get water on-to and off-of the Shoal. The first is to dredge an east-west oriented channel just to the south of Fields Point, to connect the Turning Basin to the Ship Channel. The second is to decrease the probability that a bottom water parcel will become trapped in the Turning Basin by removing the deepest part of the basin. A combination of these two designs yields the highest result in exchange between the Turning Basin and the Ship Channel. From this analysis, it appears that the most effective way to force exchange between the Edgewood Shoals and the Providence River Ship Channel is an east-west channel to act as a conduit for flow between the Ship Channel and the bottom water of the Turning Basin. However, it is also evident that decreasing the depth of the Turning Basin to an ambient depth of 2 meters may increase the vertical mixing of the water column. When both are taken into account, in Run 1c the effect is similar to dredging an access channel between the Port Edgewood Turning Basin and the Ship Channel to the south of Fields Point.

## **APPENDIX A:**

### **Extra Model Runs, Model Temperature and Currents Verification**

Two parameters were determined influential to modeled velocity results in the upper Providence River. The first parameter is bottom roughness length, or  $Z_{ob}$  in the ROMS input file. Bottom roughness length is set to determine the roughness effect from bathymetry on the water column (Shlepectin, 2005). It is a user-chosen parameter based on the application, and is a component of the logarithmic bottom drag law set in ROMS. Li and Zhong (2009) and Xu et al. (2002) set roughness height to 5mm (0.0005m) and 0.5mm (0.0005 m), respectively, for Chesapeake Bay ROMS simulations of tidally-driven stratification. The current value for bottom roughness height in NB-ROMS is 1cm (0.001 m). To test the sensitivity of the bottom roughness height parameter, three runs were performed (Figures A1, A2 and A3). Run 1 (red) kept  $Z_{ob}$  at the originally determined value of 0.01m. Run 2 (blue) decreased  $Z_{ob}$  from 0.01 m to 0.0005m, which is the value used and verified by Li and Zhong (2009) in ROMS runs in Chesapeake Bay. Run 3 increased  $Z_{ob}$  from 0.01m to 0.1 m, a factor of 10 (green).

Residual flows for these runs are shown in figures A1-A3 focusing on two time-periods and three locations. The first time period is decimal day 185-190, on which occurs a neap tide, and the second time-period is decimal day 192-197 on which occurs the spring tide. A ROMS output station just south of Save the Bay (STB, Station 25), an output station in the Port Edgewood Channel (PEC, Station 80), and an output station in the Ship Channel (Ship Channel, Station 22) were chosen for this

sensitivity analysis. U (eastward) and V (northward) velocities were obtained from the three model runs and are projected over the three time-periods for these locations.

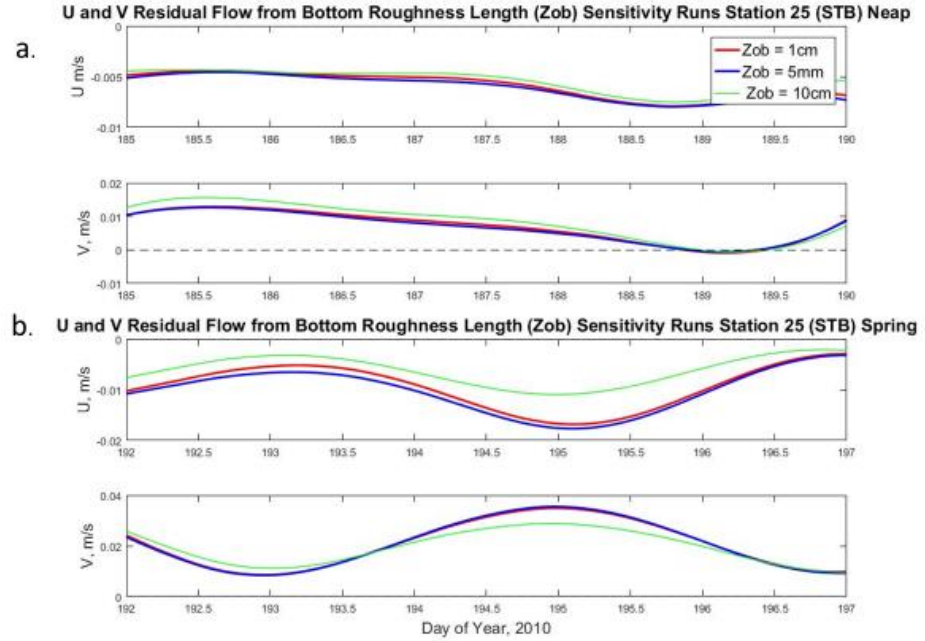


Figure A1a. U (eastward) and V (northward) residual flow over the neap tidal cycle at the Save the Bay output station in ROMS (Station 25, STB). A1b. U (eastward) and V (northward) residual flow over the spring tidal cycle at the Save the Bay output station in ROMS (Station 25, STB).

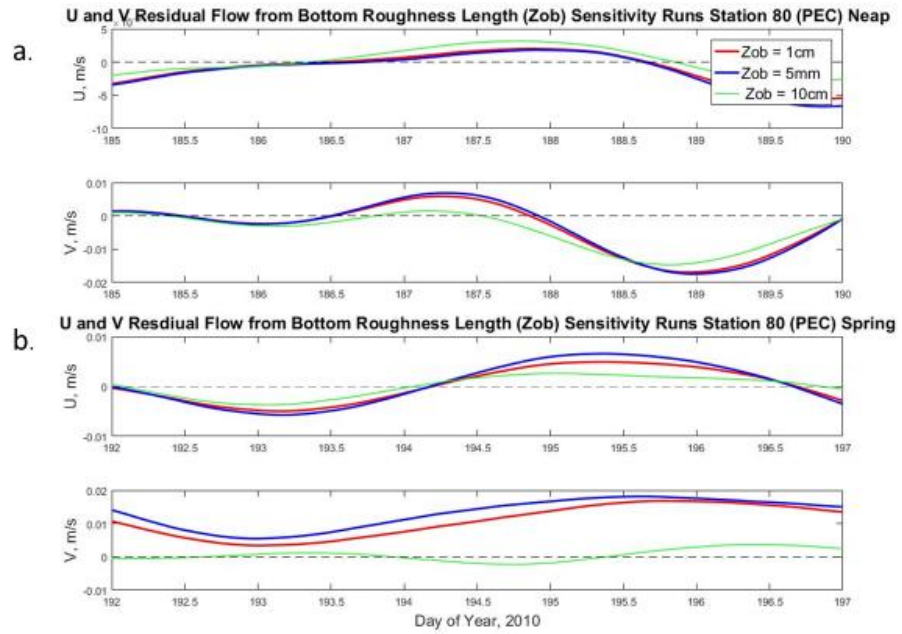


Figure A2a. U (eastward) and V (northward) residual flow in the bottom water over the neap tidal cycle at the Port Edgewood Channel output station in ROMS (Station 80, PEC). A2b. U (eastward) and V (northward) residual flow over the spring tidal cycle at the Port Edgewood Channel output station in ROMS (Station 80, PEC). The dotted line marks zero, over which the residual flow in the northward and eastward direction changes direction (northward positive, eastward positive, southward negative, westward negative).

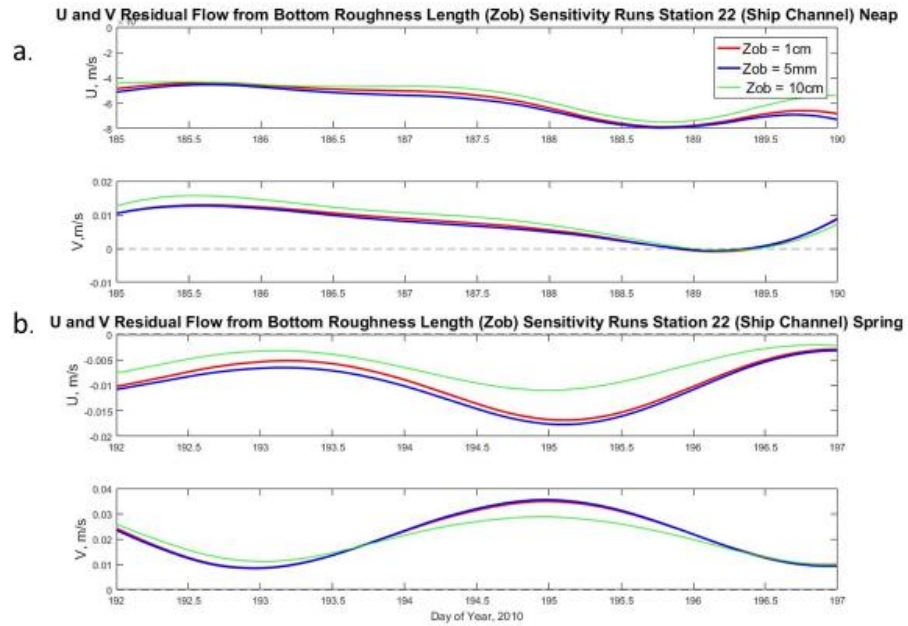


Figure A3a. U (eastward) and V (northward) residual flow in the bottom water over the neap tidal cycle at the Ship Channel output station in ROMS (Station 22, Ship Channel). A3b. U (eastward) and V (northward) residual flow over the spring tidal cycle at the Ship Channel output station in ROMS (Station 22, Ship Channel). The dotted line marks zero, over which the residual flow in the northward and eastward direction changes direction (northward positive, eastward positive, southward negative, westward negative).

There appears to be no significant difference between the observed residual flows in the parameter sensitivity runs where bottom roughness length is set to 1 cm, and 5 mm, respectively. However, when the bottom roughness length is increased by a factor of 10, from 1 cm to 10 cm, there appears to be a reduction in the amplitude of the residual flow pattern in both the northward and eastward directions. During the spring cycle at the Port Edgewood Channel output station (PEC, Station 80), the direction of residual flow reverses from net northward when the bottom roughness length is set to 1 cm and 5 mm, respectively, to net southward when the bottom roughness is increased by a factor of 10, from 1 cm to 10 cm.

While it is an interesting result, increasing the bottom roughness length to 10 cm is unrealistic for this application of the ROMS model. According to literature for ROMS applications in the Chesapeake Bay area a similar tidal-straining, partially-to-well-mixed estuary, the bottom roughness length is set to a value of less than 1 cm. Due to the small differences in flow observed in the sensitivity run between the set NB-ROMS value of 1 cm, and the Li and Zhong (2009) value of 0.5 cm, it was determined that the ROMS runs testing the parameter of bathymetric alternatives on Edgewood Shoals shall be kept at its value.

The second parameter explored in this results section is wind vs. no-wind scenarios. In order to understand the effect of variable winds on the study area of Edgewood Shoals, two runs were completed for 40 modeled days (decimal day 180-220, 2010) each during the summer of 2010. Winds were set to be uniform over the entire grid, and were obtained from observations at the NOAA PORTS Providence, Newport and Quonset sites. During the second model run, the uniform winds over the entire grid were set to zero for the entire run. Much like the model sensitivity runs for bottom roughness length, the residual flow results for wind sensitivity model runs are portrayed over two time periods, a spring cycle and a neap cycle, at three locations.

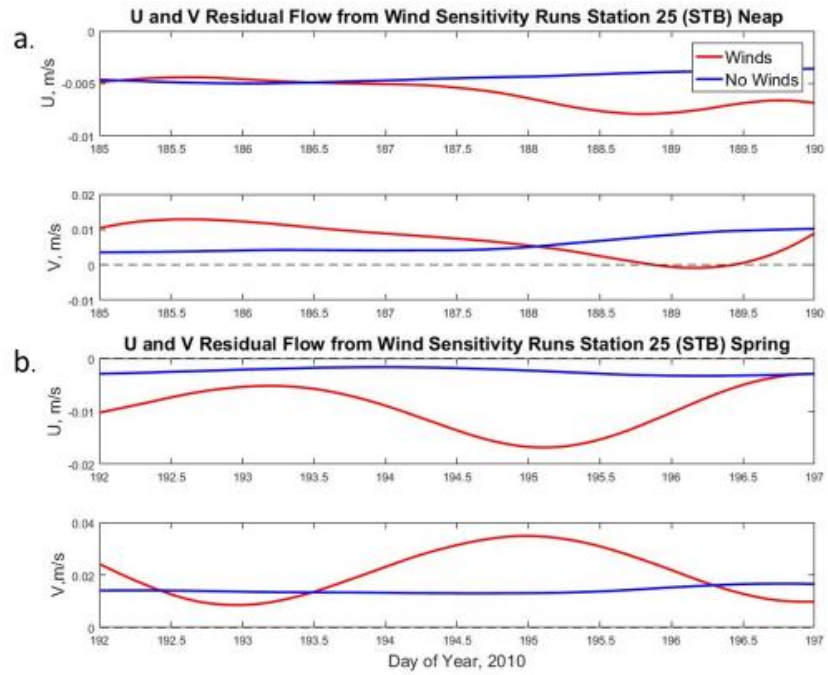


Figure A4a. U (eastward) and V (northward) residual flow over the neap tidal cycle at the Save the Bay output station in ROMS (Station 25, STB). A4b. U (eastward) and V (northward) residual flow over the spring tidal cycle at the Save the Bay output station in ROMS (Station 25, STB).

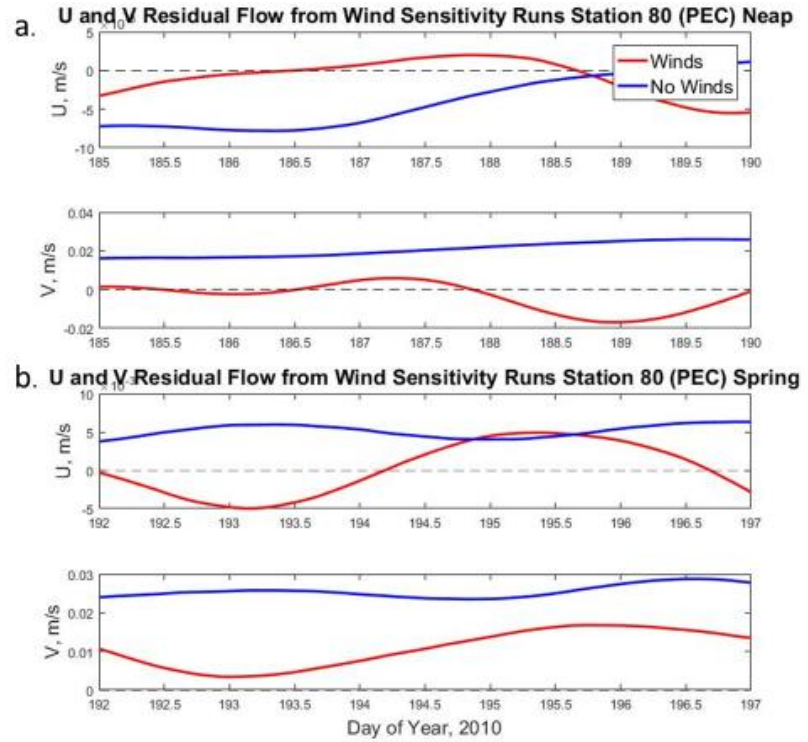


Figure A5a. U (eastward) and V (northward) residual flow over the neap tidal cycle at the Port Edgewood Channel output station in ROMS (Station 80, PEC). A5b. U (eastward) and V (northward) residual flow over the spring tidal cycle at the Port Edgewood Channel output station in ROMS (Station 80, PEC).



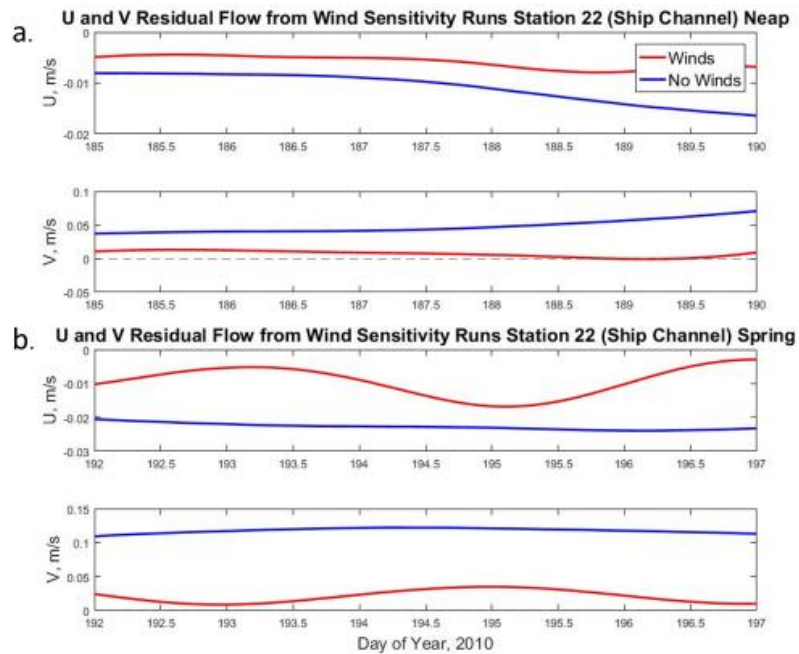
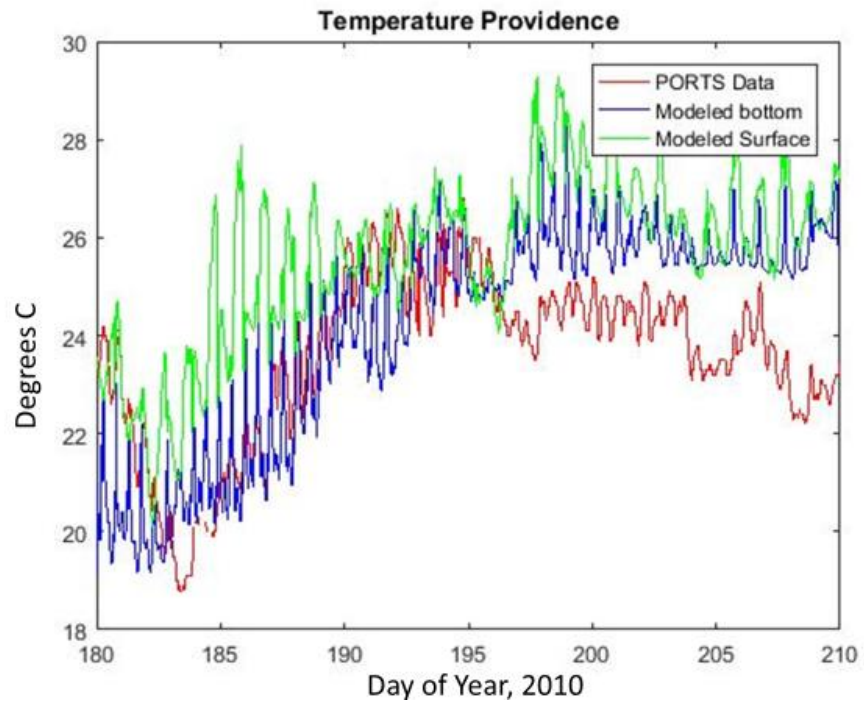


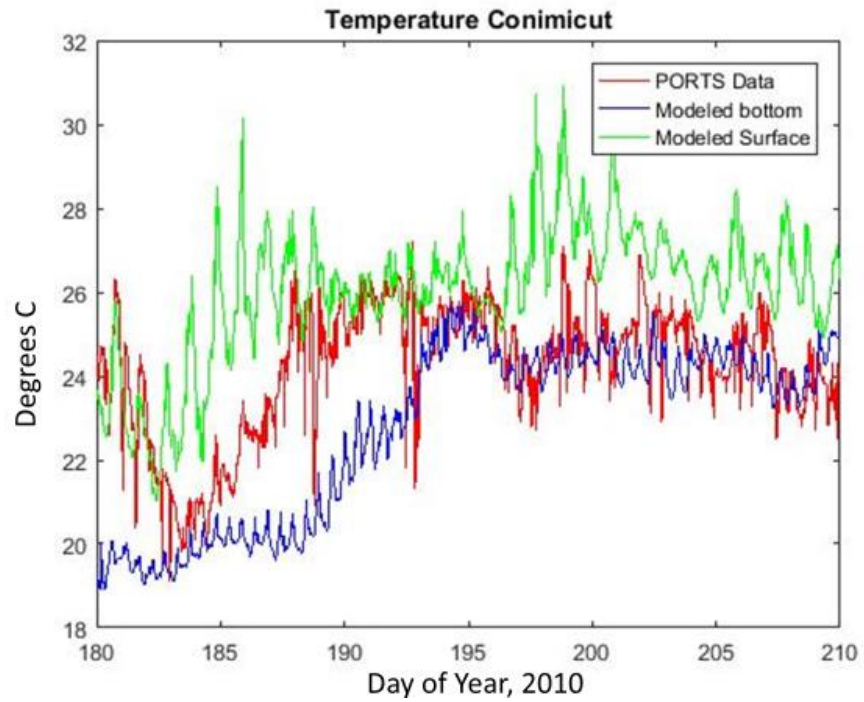
Figure A6a. U (eastward) and V (northward) residual flow over the neap tidal cycle at the Ship Channel output station in ROMS (Station 22, Ship Channel). A6b. U (eastward) and V (northward) residual flow over the spring tidal cycle at the Ship Channel output station in ROMS (Station 22, Ship Channel).

Running the model for 40 days without winds had a significant effect on the residual flows in the upper Providence River. At the Save the Bay model output station (STB, Station 25) (figure. A4a), variable winds decrease the zonal (eastward) residual flow. This effect is amplified during the spring cycle. It has been determined through this sensitivity study that winds have a significant impact on the natural flushing patterns on Edgewood Shoals, contributing to how the Shoal circulates in a real-time setting. For this reason, variable winds will be used in this study testing bathymetric induced flushing changes.

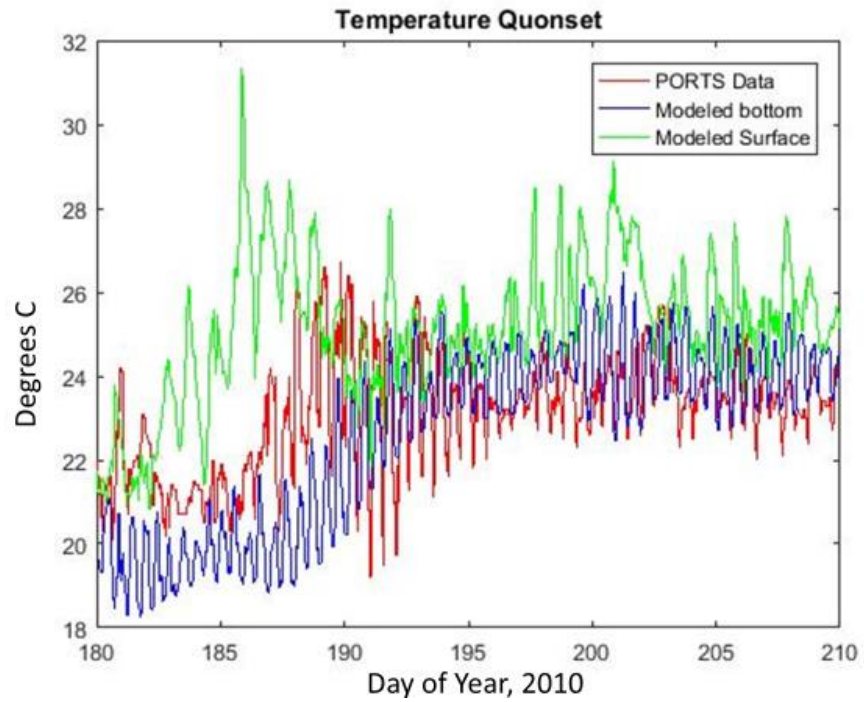
*Comparison with PORTS Temperature Data*



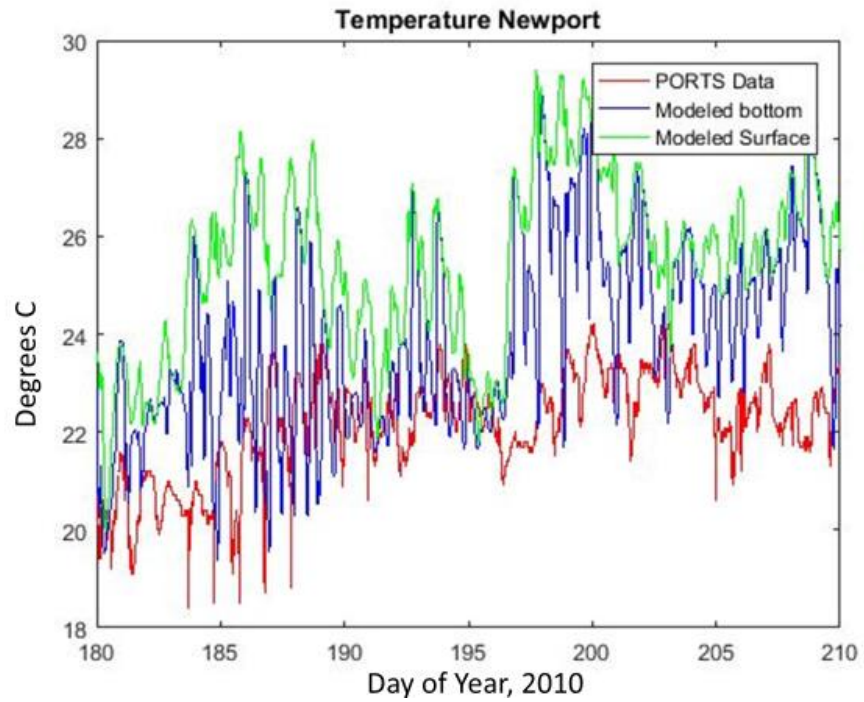
A7. Model verification for temperature at the NOAA Ports Station at Providence, RI. Red indicates the PORTS data at a depth of 0.54 meters below MLLW, whereas blue and green are output temperatures at the same location in the NB-ROMS model at the bottom, and surface, respectively.



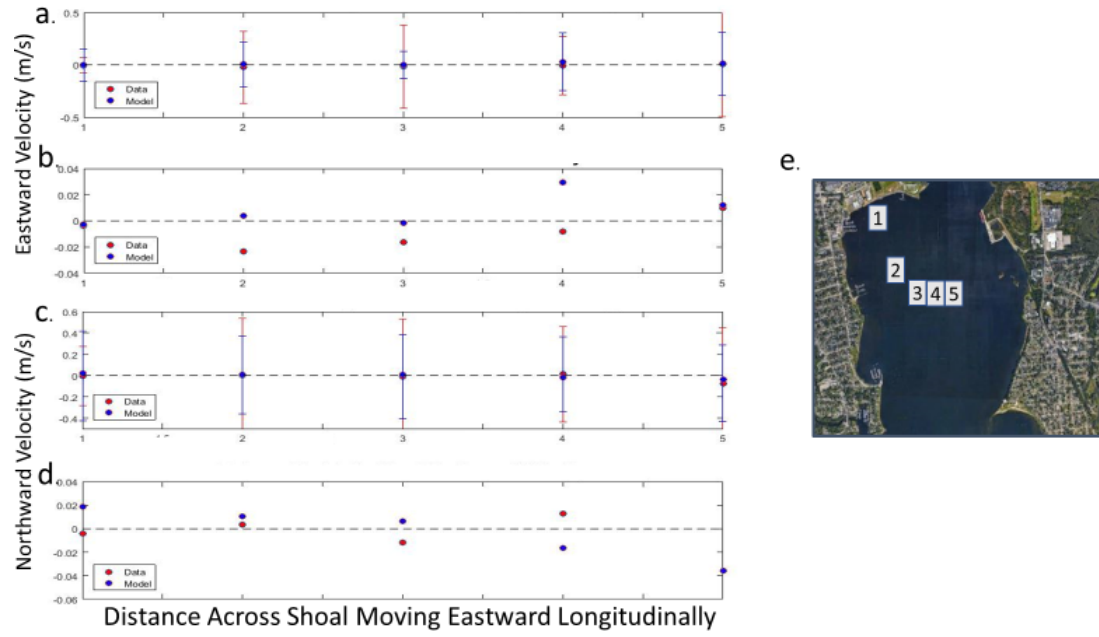
A8. Model verification for temperature at the NOAA Ports Station at Conimicut Light, Warwick, RI. Red indicates the PORTS data at a depth of 1.21 meters below MLLW, whereas blue and green are output temperatures at the same location in the NB-ROMS model at the bottom, and surface, respectively.



A9. Model verification for temperature at the NOAA Ports Station at Quonset, in North Kingstown, RI. Red indicates the PORTS data at a depth of 2.1 meters below MLLW, whereas blue and green are output temperatures at the same location in the NB-ROMS model at the bottom, and surface, respectively.



A10. Model verification for temperature at the NOAA Ports Station at Goat Island, in Newport, RI. Red indicates the PORTS data at 1.31 meters below MLLW, whereas blue and green are output temperatures at the same location in the NB-ROMS model at the bottom, and surface, respectively.



A11. Model verification for temporally averaged ROMS residual (b, d) and instantaneous (a, c) current variability compared to the temporally averaged 2010 tilt current meter deployment. (e.) the locations (1-5) of each station for model verification.

## **Appendix B:**

### **Edgewood Shoals, Providence River Data Report: TCM Deployment August 2018- November 2018**

G. E. Medley

#### **Introduction/Methods**

This Tilt Current Meter (TCM) deployment (figure B1) is a repeat deployment of the 2010 TCM Observational data collection on Edgewood Shoals by C. Balt and C. Kincaid (Balt, 2011; Kincaid, 2012), with two additional points added to the original data set near the outfall of the Pawtuxet River. Two types of TCM's were used during this deployment. The first type is a Lowell Instruments Tilt Current Meter, with an internal compass and accelerometer to compute velocity and direction within the instrument. The second type is a SeaHorse Tilt Current Meter designed by V. Sheremet (Manning and Sheremet, 2008), using HOBO Instruments accelerometers attached to the end of a buoyant PVC pipe, and using calibration and correction factors to post-process tilt and speed into water velocity and direction. Current meters were deployed off of a URI skiff on August 23<sup>rd</sup> beginning at 1300 h EDT (1700 h GMT).

Table 1:

Instrument Name	Longitude	Latitude	Depth (meters)
ES01	-71.3825	41.7839	2.0
ES02	-71.3858	41.7825	4.5
ES03	-71.3875	41.7804	2.6
ES04 (LOST)	-71.3872	41.7779	2.0
ES05 (LOST)	-71.3841	41.7775	4.6
ES06	-71.3809	41.7779	2.5
ES07	-71.3782	41.7785	2.5
ES08	-71.3782	41.7811	2.5
ES09	-71.3772	41.7838	3.0
ES10	-71.3780	41.7854	4.0
ES11	-71.3820	41.7708	3.5
ES12	-71.3826	41.7617	3.0

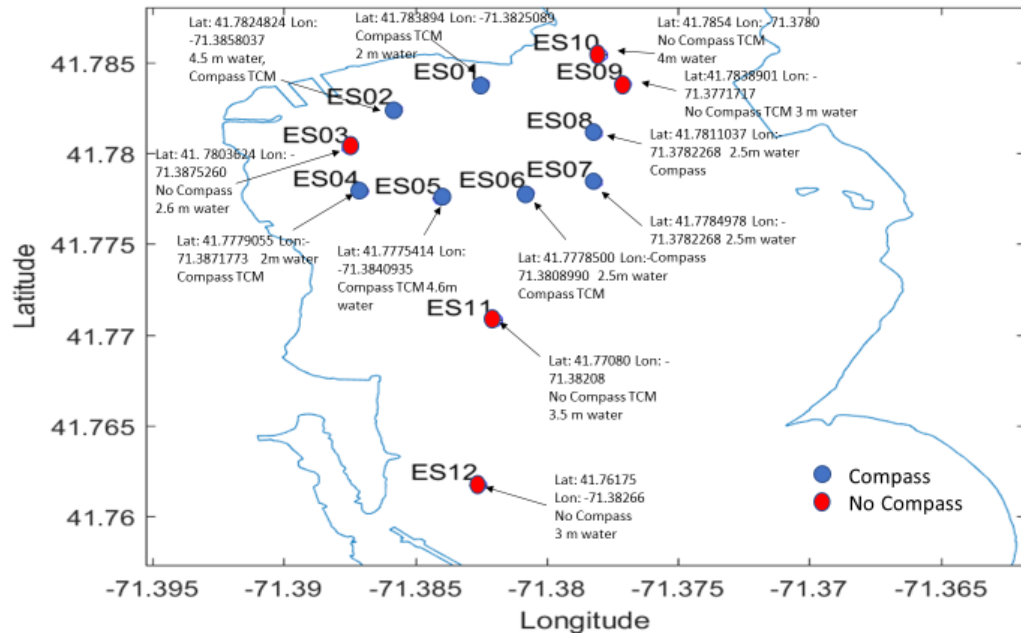


Figure B1: Schematic of the 2018 TCM deployment locations. Red symbolizes TCM's without internal compasses (Manning and Sheremet, 2008) and blue symbolizes TCM's with internal compasses (Lowell, 2005).



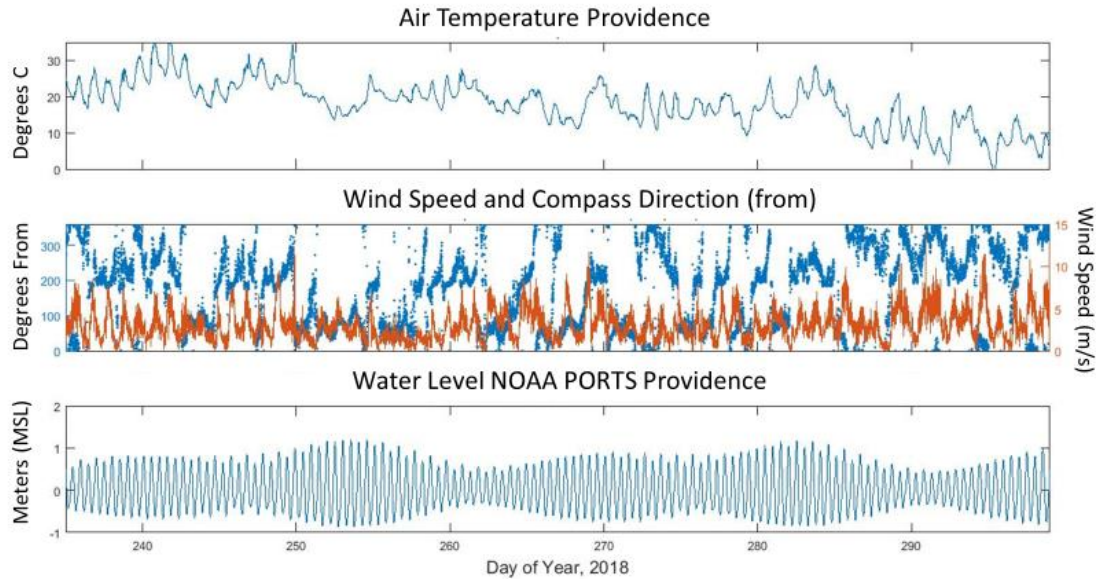


Figure B2: Air Temperature, Wind speed and direction, and water level observational data from NOAA PORTS Station 8454000 (Providence, RI) for the duration of the deployment.

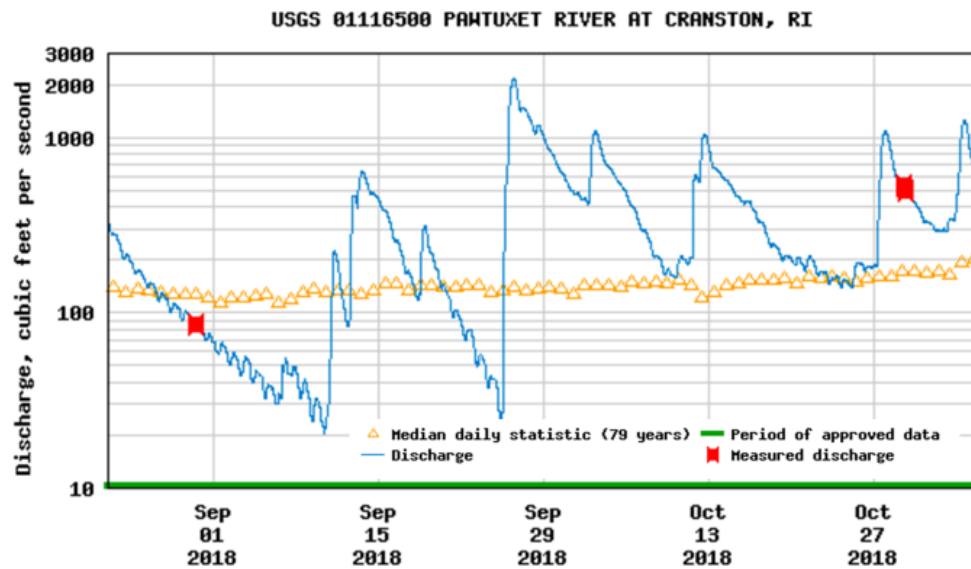


Figure B3: USGS Discharge (CFS) from the Pawtuxet River at Cranston, RI during the period of instrument deployment.

Notable wind events occurred between decimal day 249 and 251 (9/6-9/8) (figure B2), and decimal day 294 and 296 (10/21-20/23). A discharge event of 2000

CFS from the Pawtuxet River occurred between decimal day 270 and 273 (9/27 and 9/30) (figure B3).

## **Results**

The results will be presented as follows: All TCM data with compasses will be analyzed for residual and instantaneous means, absolute maxima, standard deviation and variance. TCM's with compasses will then be analyzed individually by location based on significant environmental events: one high discharge event from the Pawtuxet River, one spring tide cycle, one neap tide cycle, one strong southerly (northward) wind event, and one strong northerly (southward) wind event. TCM's without compasses will be presented as raw, unprocessed data.

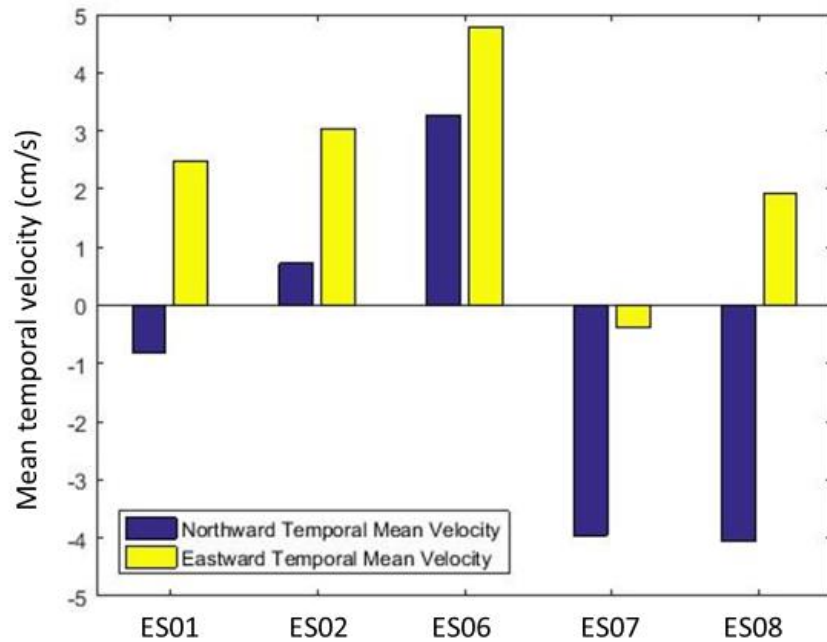


Figure B4: Graph of mean temporal currents over entire deployment. Northward velocities are represented in blue while eastward velocities are represented in yellow. ES01: Save the Bay Dock; ES02: Turning Basin; ES06: Adjacent to Port Edgewood Channel; ES07: Between Port Edgewood Channel and Ship Channel; ES08: Adjacent to Ship Channel.

The temporal mean flows observed at ES01, ES02, ES06, ES07 and ES08 indicate stronger mean flows (southward) near the edge of the Ship Channel (ES07 and ES08), reaching -4 cm/s (figure B4). During this deployment, only one TCM (ES07) experienced a net-westward flow, which is expected in the residual gyre. ES06 showed the highest eastward mean temporal flow, at 4.8 cm/s.

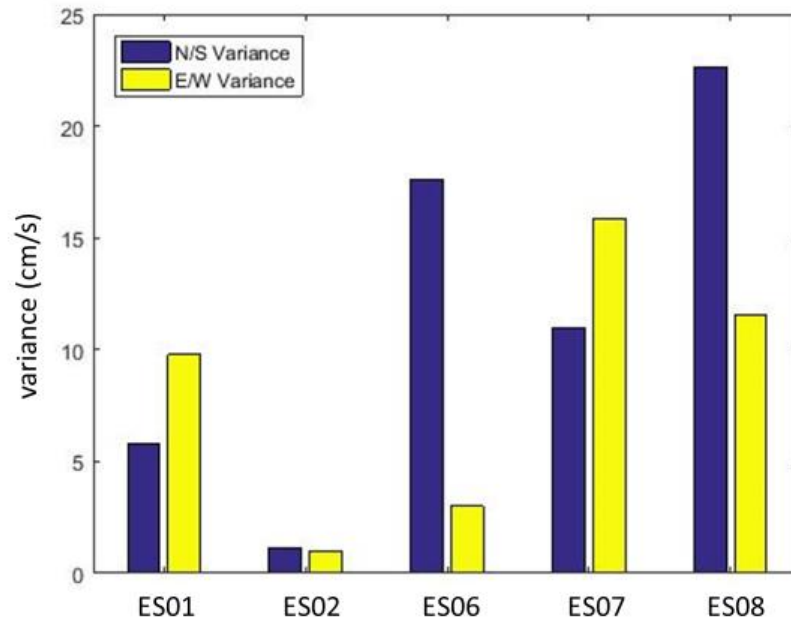


Figure B5: Graph of instantaneous variability (variance) for north/south velocities (blue) and east-west velocities (yellow). ES01: Save the Bay Dock; ES02: Turning Basin; ES06: Adjacent to Port Edgewood Channel; ES07 Between Port Edgewood Channel and Ship Channel; ES08: Adjacent to Ship Channel.

The TCM station that experiences the smallest north/south and east/west variance (less than 3 cm/s) in both northward and eastward velocity is ES02, in the Turning Basin (figure B5). The largest north/south variance is observed adjacent to the Ship Channel (23 cm/s). The TCM adjacent to the Port Edgewood Channel also has a strong north/south variance, at 18 cm/s, but a relatively small east-west variance at 3.5 cm/s. ES01, at the Save the Bay dock, shows a 10 cm/s variance in the east-west direction and a 6 cm/s variance in the north-south direction.

## Wind Events (Decimal Days 249.9, 294.7)

### ES01: Save the Bay Dock

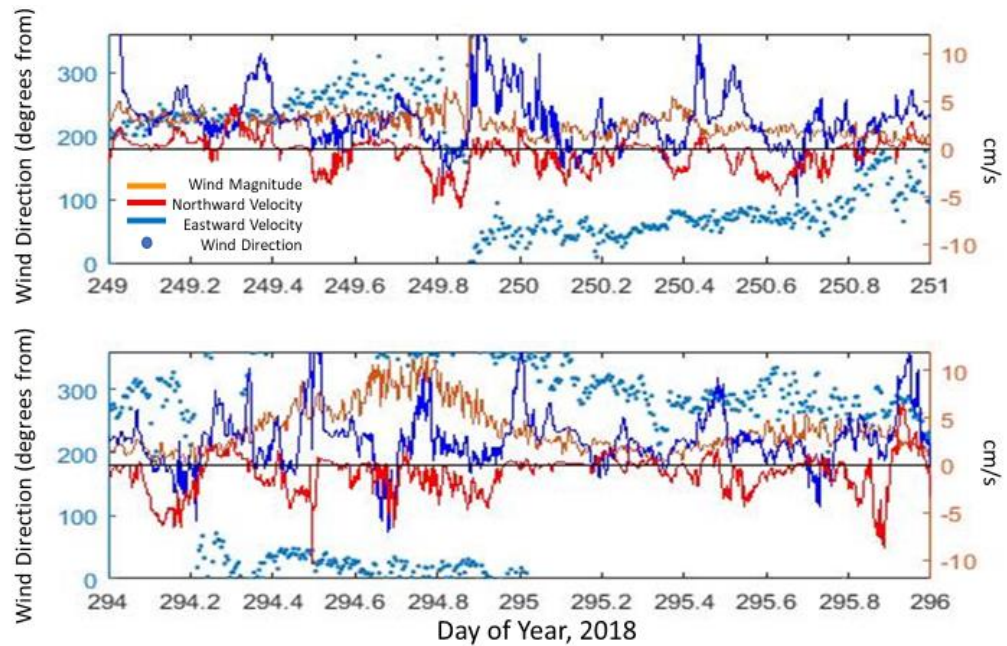


Figure B6: Time series from the TCM at Save the Bay Dock covering two wind events, decimal day 249-251 (southerly) and 294-296 (northerly). The orange line represents the wind magnitude, in cm/s. The blue dots represent the wind direction (from), and the red and blue lines represent water velocities, northward and eastward, respectively.

At the Save the Bay dock (ES01) (figure B6) the southerly wind event causes an eastward increase in the velocities passing this TCM. An increase in the eastward component at this station is indicative of a gyre spin-up. The northerly (southward) wind event has a more complex effect on the bottom water at Save the Bay dock. At the onset of the wind event (decimal day 294.6) there is a notable spike in the southward and westward velocity components, which indicates a gyre-reverse. Immediately following the onset of this wind event, the eastward component increases, and the southward component remains the same, indicating a potential flush of the shoal.

## ES02: Port Edgewood Turning Basin

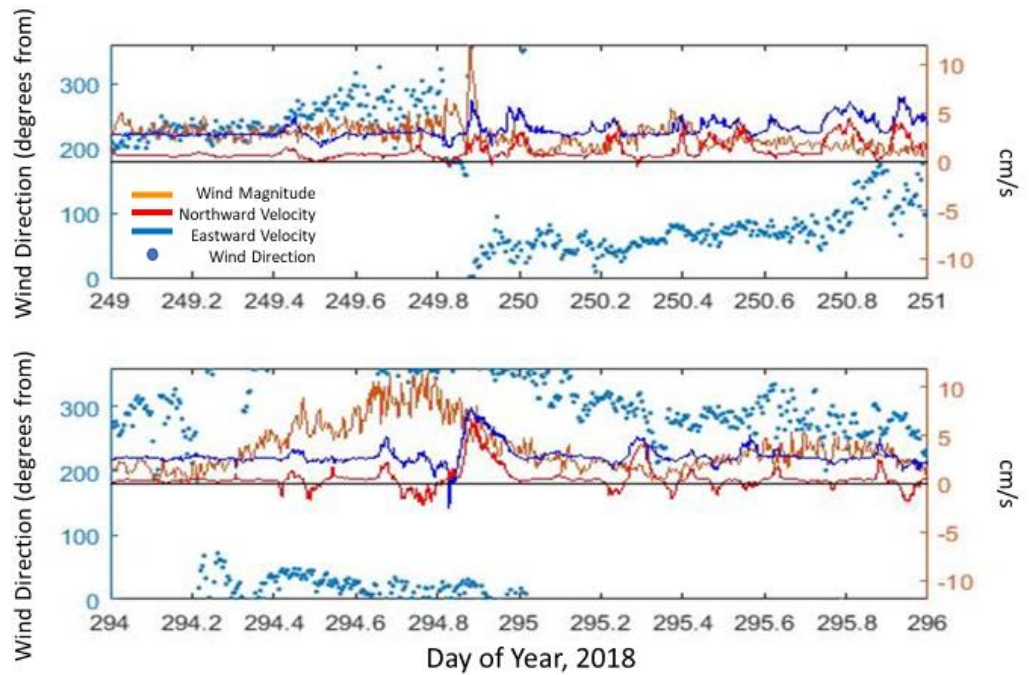


Figure B7: Time series from the TCM in the Port Edgewood Turning Basin covering two wind events, decimal day 249-251 (southerly) and 294-296 (northerly). The orange line represents the wind magnitude, in cm/s. The blue dots represent the wind direction (from), and the red and blue lines represent water velocities, northward and eastward, respectively.

The instantaneous velocities in the Turning Basin (figure B7) average below 5 cm/s throughout the duration of the deployment. During the onset of the southerly wind event, a notable northward and eastward pulse is visible in the TCM data (5-6 cm/s). During the northerly (southward) wind event, the onset of the event does not appear to affect the bottom water of the turning basin. However, on decimal day 294.9, during the latter part of the wind event, a notable increase is observed in both the northward and eastward velocity components (5-7 cm/s). This is indicative of a potential gyre spin-up.

## ES06: Immediately East of Port Edgewood Channel

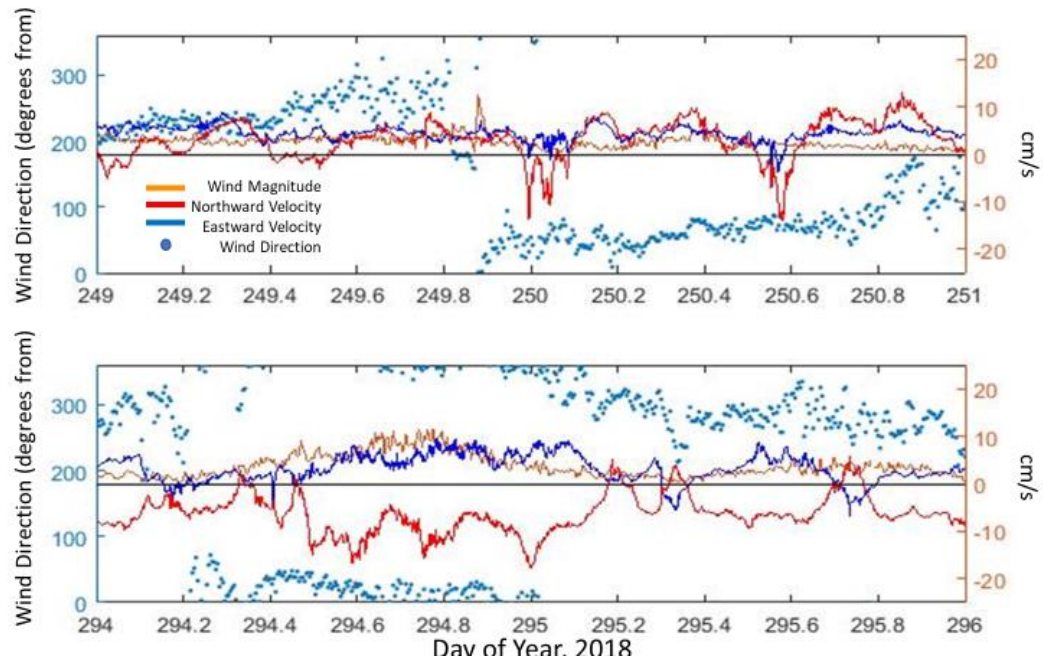


Figure B7: Time series from the TCM immediately east of the Port Edgewood Channel covering two wind events, decimal day 249-251 (southerly) and 294-296 (northerly). The orange line represents the wind magnitude, in cm/s. The blue dots represent the wind direction (from), and the red and blue lines represent water velocities, northward and eastward, respectively.

It is difficult to discern an effect at this station from the southerly (northward) wind event occurring between decimal day 249 and 251. However, during the northerly (southward) wind event, a series of strong ( $>10$  cm/s) southward pulses are visible in the bottom water at this station. The eastward component increases, yet remains below 7 cm/s. Moving towards the Ship Channel, (ES06, ES07, ES08) the north/south water velocity component dominates the east/west velocity component, as is beginning to be observed by the data in figure B7.



ES07: Between ES06 and ES08

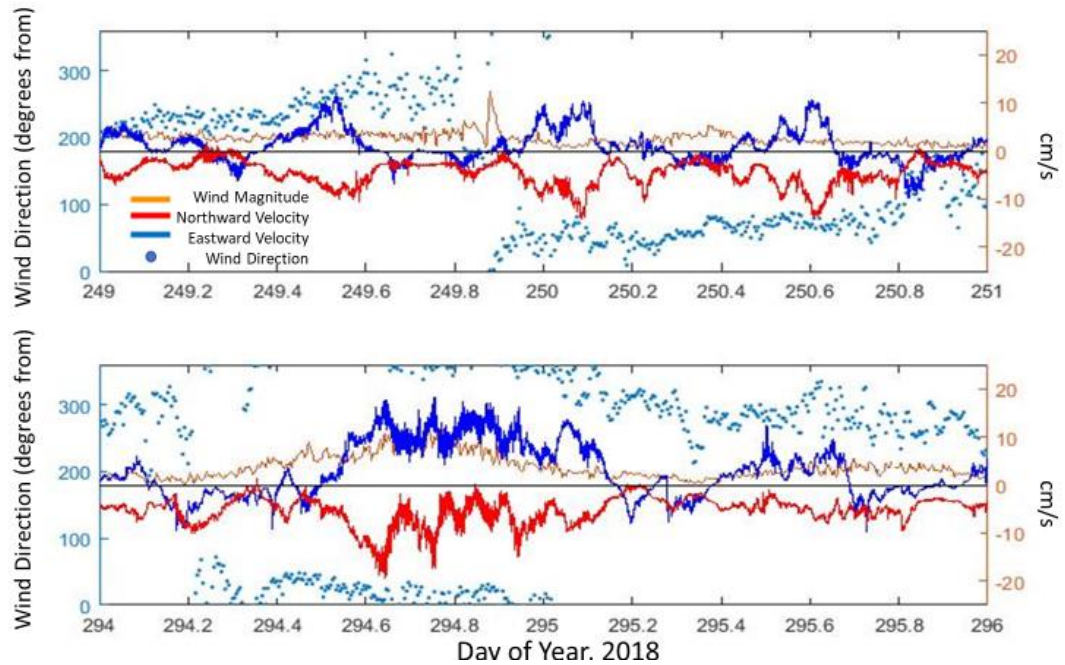


Figure B8: Time series from the TCM between the Port Edgewood Channel and the Ship Channel covering two wind events, decimal day 249-251 (southerly) and 294-296 (northerly). The orange line represents the wind magnitude, in cm/s. The blue dots represent the wind direction (from), and the red and blue lines represent water velocities, northward and eastward, respectively.

Much like at ES06 (immediately to the east of the Port Edgewood Channel) ES07 experiences a similar pattern of southward flow increase (peaking at 19 cm/s) during the northerly (southward) wind event. Interestingly, this station also features a strong increase in eastward flow (10-15 cm/s) during this wind event as well. This indicates a gyre breakdown, and a potential flush of the Shoal during a northerly (southward) wind event.



## ES08: Ship Channel Edge

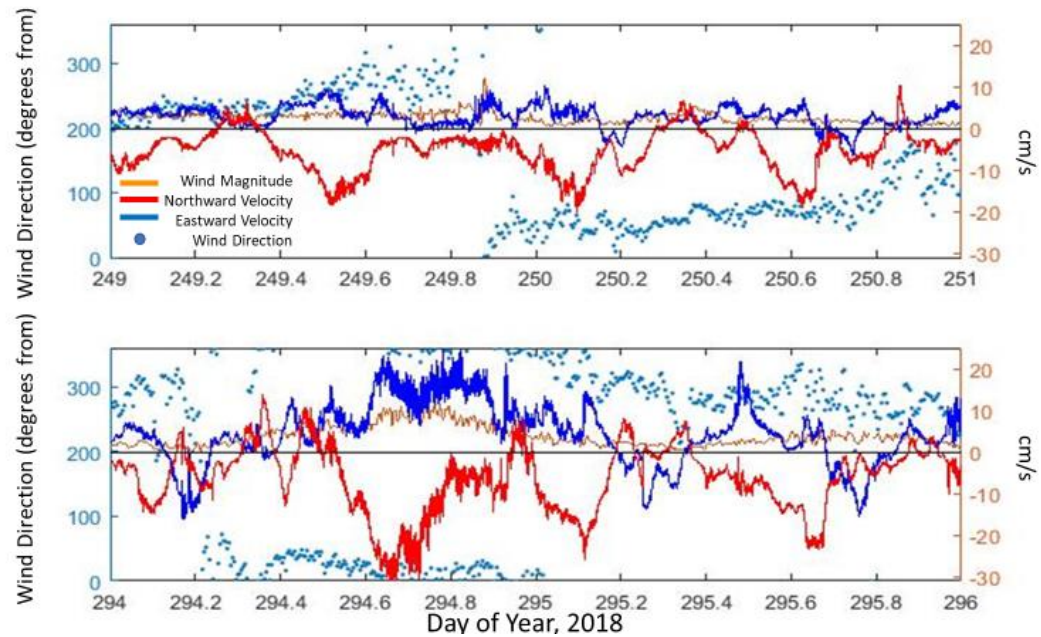


Figure B7: Time series from the TCM at the Ship Channel Edge covering two wind events, decimal day 249-251 (southerly) and 294-296 (northerly). The orange line represents the wind magnitude, in cm/s. The blue dots represent the wind direction (from), and the red and blue lines represent water velocities, northward and eastward, respectively.

The Ship Channel Edge experiences the highest velocities of the compass TCM deployment. During the southerly (northward) wind event, a slight increase in the eastward component is observed, however it is relatively insignificant (6 cm/s) when compared over the larger time-series. Notably, a strong southward pulse (29-30 cm/s) is visible during the onset of the northerly (southward) wind event. This pulse is accompanied by a series of strong eastward (20 cm/s) pulses.

*Runoff Event (decimal day 270)*

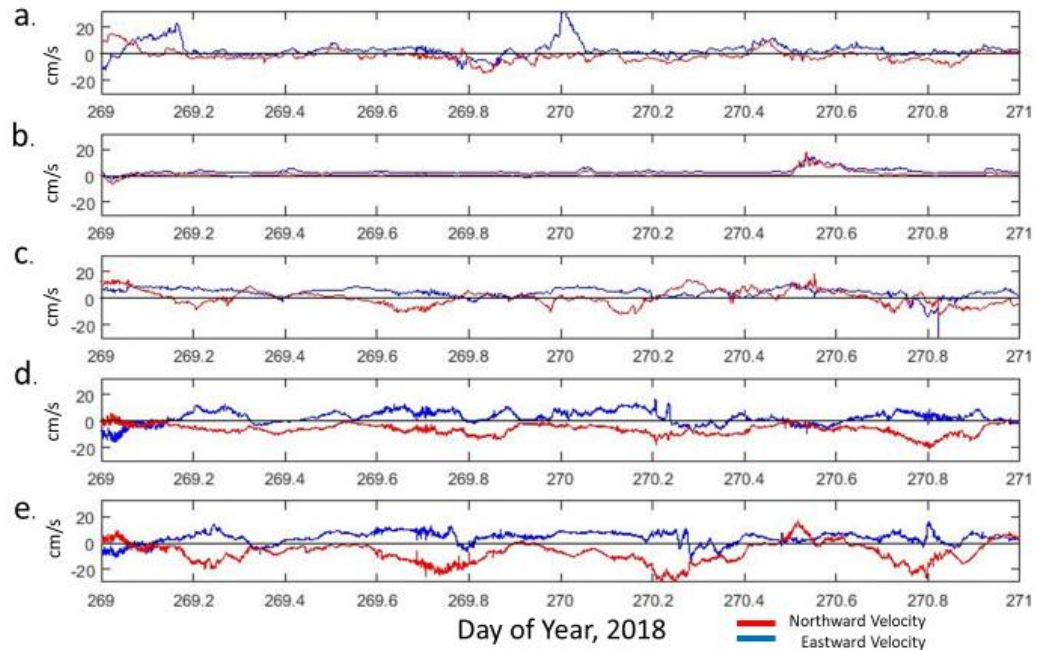


Figure B9: Time series from the 5 compass TCM's covering the time-period in which a discharge event (2000 CFS) from the Pawtuxet River occurred. (a.) ES01: Save the Bay Dock; (b.) ES02: Turning Basin; (c.) ES06: Adjacent to Port Edgewood Channel; (d.) ES07 Between Port Edgewood Channel and Ship Channel; (e.) ES08: Adjacent to Ship Channel.

A spike in the eastward velocity is visible in the TCM observations from ES01: Save the Bay Dock (figure B9a) immediately following the discharge event. This increase in eastward flow in the northern part of the shoal indicates a spin-up of the gyre during a Pawtuxet River discharge event. There is a slight increase in the southward (negative northward) velocities at ES06 (immediately east of PEC), ES07 (between PEC and Ship Channel) and ES08 (adjacent to ship channel) (figure B9c, B9d, B9e). An increase of 5 cm/s northward and eastward is observed in the Turning Basin (B9b), which is likely to be attributed to this discharge event. An increase in the northward and eastward component in the Turning Basin indicates a gyre spin-up.

*Raw Data: ES03, ES09, ES10, ES11, ES12*

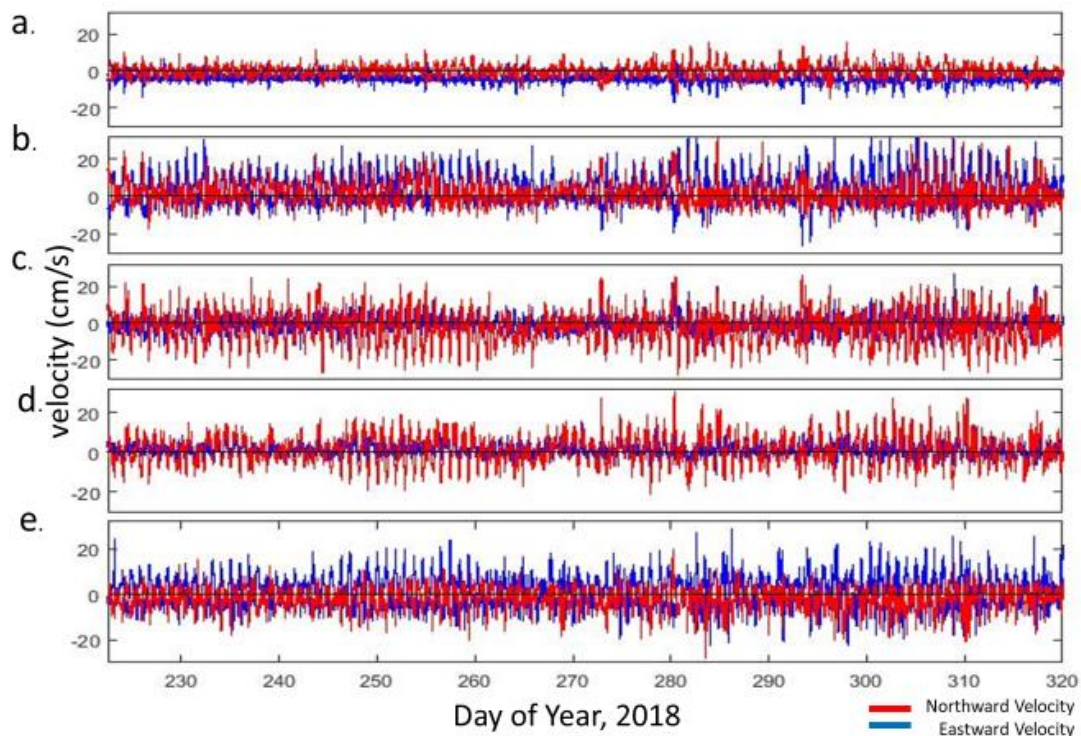


Figure B10: Raw, unprocessed data from (a.) ES03: west of Turning Basin; (b.) ES09: Edge of Ship Channel; (c.) ES10: immediately east of Fields Point (d.) ES11: southern Shoal; (e.) ES12: mouth of Pawtuxet River. Blue lines are indicative of eastward velocity and red lines are indicative of northward velocity. These data are unprocessed, and may have directional errors.

## Appendix C:

### Results of Buoyancy-driven flow dredging experiment 3a

**Total Floats On Edgewood Shoals Over 3 Days Neap Tide - Maximum Dredging Slope Creation**

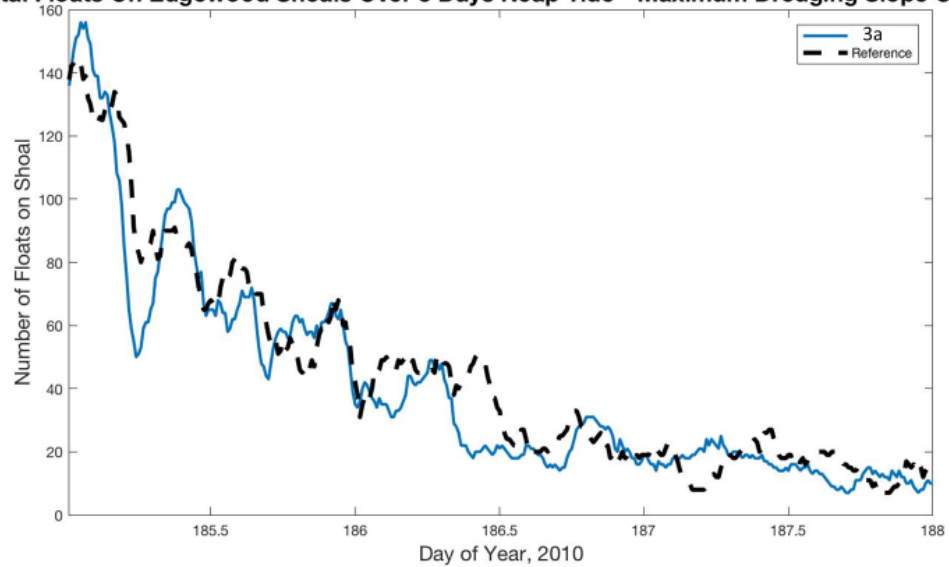


Figure C1: Time-series of drifters in the analysis box on Edgewood Shoals (figure 10) compared between the reference case (black, dotted line) and Run 3a (blue solid line).

**Surface Dye Concentration over 3 Days, Neap Tide -Maximum Dredging Slope Creation**

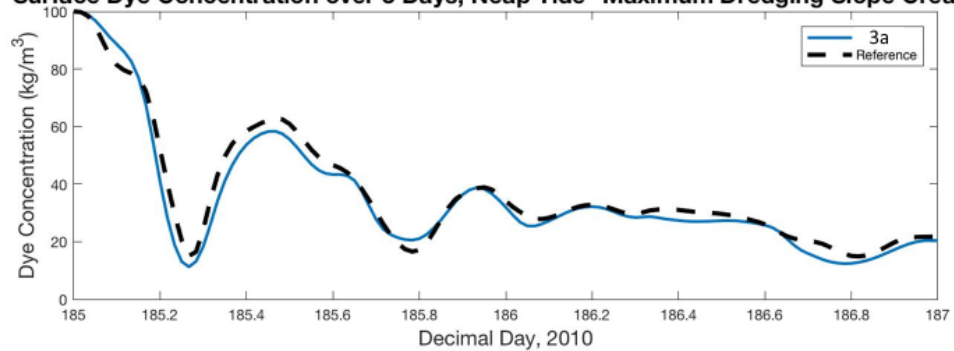


Figure C2: Time-series of dye concentration in the analysis box on Edgewood Shoal (figure 10) compared between the reference case (black, dotted line) and Run 3a (blue solid line).

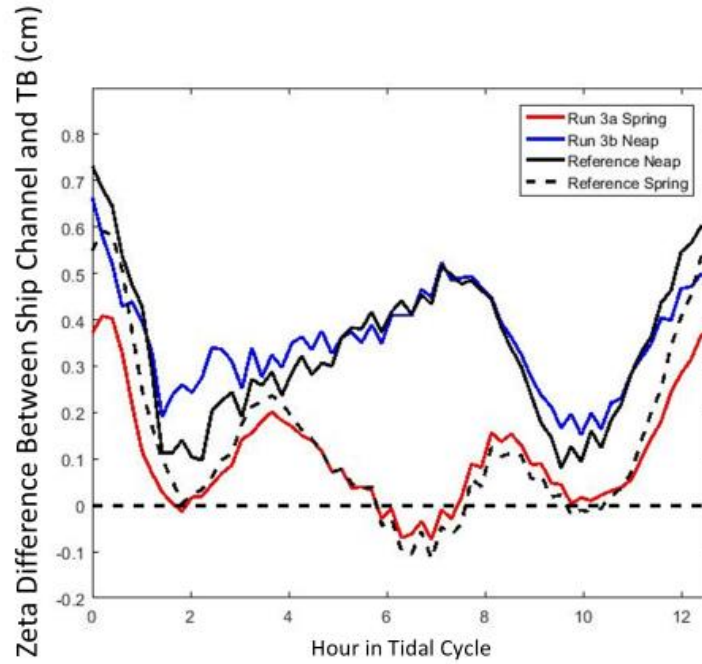


Figure C3: Modeled surface elevation (zeta) difference between the Ship Channel and the Turning Basin (TB) on Edgewood Shoal over 6 averaged neap and spring cycles, for each dredging scenario (Run 3a spring tide in red, 3a neap tide in blue reference neap tide in solid black, and reference spring tide in dotted black). A negative value indicates that the Shoal surface elevation is higher than the Ship Channel, whereas a positive value indicates that the Ship Channel has a higher surface elevation than the Shoal.

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